

Mechanical Testing of Engineering Materials

By Kyriakos Komvopoulos

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Sneak Preview

MECHANICAL TESTING OF ENGINEERING MATERIALS

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Preface



The mechanical response of materials to different external loadings is of great importance to many fields of science, engineering, and industry. Structural failure is realized when the functionality of engineering components has been depleted. In general, there are three main reasons for a component to become dysfunctional—excessive (elastic or inelastic) deformation, fracture, and wear. Excessive elastic deformation is controlled by the elastic properties of the material, such as elastic modulus, and may occur under loading conditions of stable equilibrium (e.g., excessive deflection of a beam), unstable equilibrium (e.g., buckling of a column), and brittle fracture. Excessive inelastic deformation depends on plastic material properties, such as ultimate tensile strength, strain hardening, and hardness, and may occur under loading conditions conducive to fatigue (a process involving alternating stresses (or strain) that induce crack initiation from stress raisers or defects in the material followed by crack growth), ductile fracture due to excessive accumulation of plastic deformation, and creep (a time-dependent deformation process encountered with viscoelastic materials and elastic-plastic materials at elevated temperatures subjected to a constant stress). Material degradation may also occur as a result of mechanical wear arising at contact interfaces of load-bearing components when the transmitted contact stresses are comparable of the material hardness. It is therefore important to not only know how the mechanical properties control the material response to a certain external force, but also have knowledge of standard mechanical testing methods for measuring different material properties.

Chapter 1 is devoted to the modification of the material microstructure by heat treatment. The chapter shows how equilibrium phase diagrams and time-temperature-transformation diagrams can be used to predict steel microstructures after a certain type of heat treatment. Chapter 2 is focused on hardness measurement and the interpretation of the hardness data in terms of microstructure differences. Chapter 3 provides insight into the extraction of elastic and plastic material properties of different materials from uniaxial loading experiments. Chapter 4 treats fracture toughness measurement by impact testing and correlation of toughness differences to microstructure variations induced by heat treatment.

The objective of Chapter 5 is the mechanical behavior of viscoelastic materials, particularly microstructure effects on stress-strain and stress relaxation responses. Deformation due to cyclic loading is the theme of Chapter 6. Special attention is given to analyzing the data in the context of cyclic hardening (softening), plastic shakedown (constant plastic strain accumulation per cycle), and ratcheting (continuous accumulation of plasticity). The purpose of Chapter 7 is to illustrate how to perform strain-control fatigue tests and how to correlate the measured fatigue properties to microstructure characteristics. Wear testing is the theme of Chapter 8, particularly the recognition of different lubrication regimes, seizure mechanisms,

lubricant behavior, and effect of load, temperature, and sliding speed on friction and wear properties of bearing materials.

The sequence of the experiments included in this book is typical of most books covering this topic. A set of questions is included at the end of each chapter, which can be used to design laboratory assignments. A report template and a rubric for evaluating laboratory reports are included in Appendices A and B, respectively. It is presumed that the students who use this book have had elementary courses on mechanics and materials sciences and, therefore, are familiar with such concepts as force and moment equilibrium, stress, strain, steel microstructures, and phase diagrams. They should also be familiar with basic statistics and data acquisition and processing.

This book should be a valuable supplement to an undergraduate-level course on mechanical behavior of materials. The emphasis is on mechanical testing according to established standards and the development of comprehensive reports of the obtained measurements. In addition to the necessary background and representative results, the book provides essential steps for carrying out each test. The coverage includes experiments drawn from the most important topics of an undergraduate course on mechanical behavior of materials.

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Acknowledgments



The idea for this book emerged after teaching the undergraduate course on mechanical behavior of materials at the University of California at Berkeley for more than 20 years, recognizing the lack of understanding of basic concepts in the absence of hands-on experience and difficulties of the students to use classroom material to explain experimental findings in a comprehensive manner. The book reflects the author's strong commitment to promote excellence in undergraduate teaching at UC Berkeley and to elevate student understanding of materials behavior.

This book would not have been possible without the tireless efforts of many of my research students, who took precious times from their research to assist me in developing the experiments presented in this book. I am greatly indebted to H. Zhang, H. Xiang, N. Wang, X. Yin, Q. Cheng, Z. Song, H. Xu, and A. Poulizac who not only played pivotal roles in setting up the experiments and obtaining the representative results included in this book, but also supervising the students during the laboratory sessions over the past year and grading their reports.

I also wish to acknowledge the support and encouragement provided by my Department. I especially thank Professor A. P. Pisano, Chair of the Department of Mechanical Engineering, for his continued interest on this project and for raising the funds to renovate the space where these laboratories are hosted. I am also grateful to my colleagues Professors L. A. Pruitt and H. Dharan for donating an axial loading machine and an impact tester, respectively, for the experiments and their support throughout my efforts to create these laboratories. Lastly, my thanks go to Mr. S. McCormick for technical assistance, equipment service and upgrading, specimen fabrication, laboratory coordination, and, especially, for overseeing the work of my students during the development of the experiments.

Chapter 1: Heat Treatment



1.1. BACKGROUND

Some basic information about phase diagrams and time-temperature-transformation (TTT) diagrams of steels is presented first as background material for the heat treatment part of this lab. Information for heat treatment of various carbon steels can be found in the Appendix 1A.

1.1.1. Phase Diagrams

The equilibrium phase diagram of Fe-C alloy system is shown in Fig. 1.1 [1].

At eutectoid position (0.76 wt% carbon composition, 748°C), the alloy undergoes the following phase transformation:

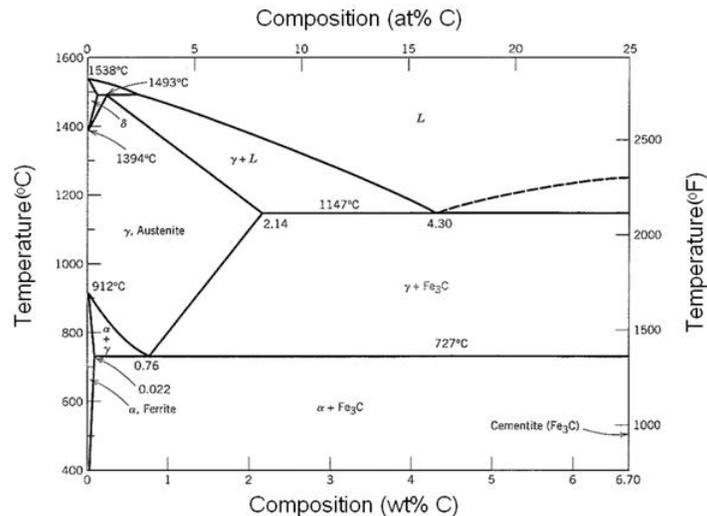


Fig. 1.1. Equilibrium phase diagram of carbon steel [1].

If the composition is exactly the eutectoid composition (Fig. 1.2(a)), solid-solid phase transformation will occur upon cooling below 748°C, resulting in the formation of pearlite (Fig. 1.2(b)) [1]. However, if the composition is hypoeutectoid (Fig. 1.3(a)), then α phase will form first, while cementite will form after cooling below 748°C, resulting in a mixture of pearlite and α ferrite (Fig. 1.3(b)) [1].

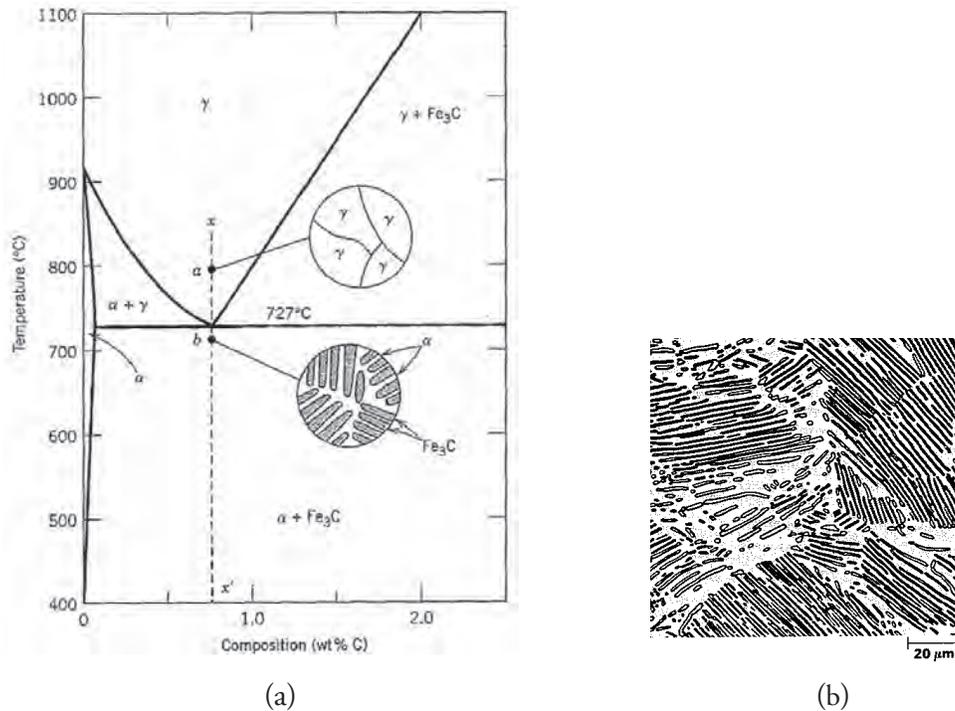


Fig. 1.2. (a) Phase diagram of eutectoid carbon steel and (b) pearlite microstructure [1].

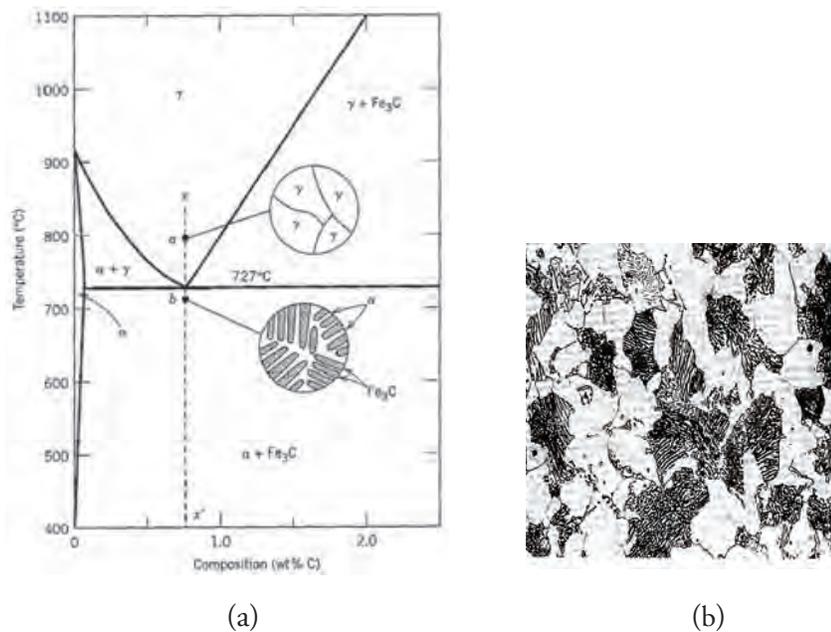


Fig. 1.3. (a) Phase diagram of hypoeutectoid carbon steel and (b) microstructure consisting of pearlite and a ferrite [1].

In the case of hypereutectoid composition (Fig. 1.4(a)), cementite will form first, whereas α ferrite will form upon cooling below 748°C, producing a mixture of pearlite and cementite (Fig. 1.4(b)) [1].

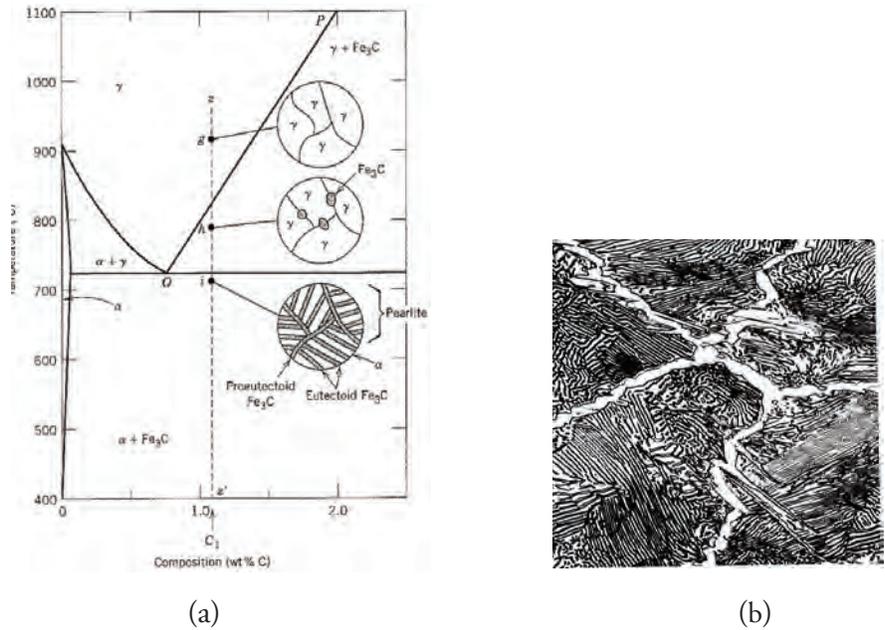


Fig. 1.4. (a) Phase diagram of hypoeutectoid carbon steel and (b) microstructure consisting of pearlite and cementite [1].

1.1.2. Time-Temperature-Transformation (TTT) Diagrams

Phase transformation during heat treatment is also controlled by the cooling rate. At a fixed temperature, it takes certain time to complete the phase transformation. By plotting the phase transformation begin time and the 50% and 100% complete times as functions of time, we can obtain the three curves shown in Fig. 1.5 [1].

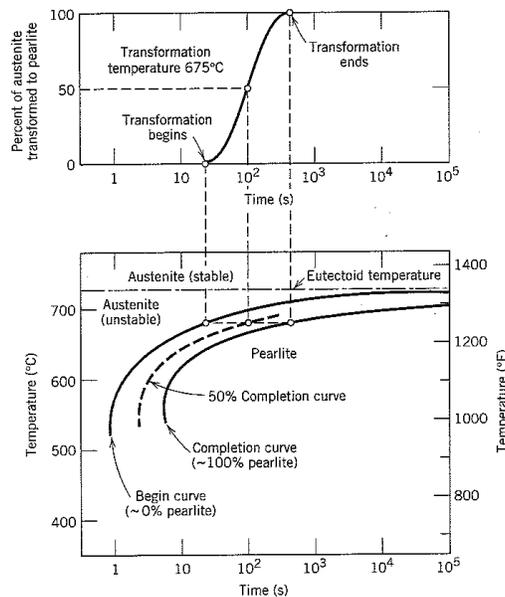


Fig. 1.5. Time-Temperature-Transformation (TTT) diagram of eutectoid carbon steel [1].

Figure 1.6 shows the time-temperature-transformation (TTT) phase diagram of eutectoid carbon steel. If cooling from above 720°C is rapid (e.g., less than 5 s), the material does not have enough time to go through equilibrium phase transformation. Instead, the austenite phase transforms to a metastable martensite phase. This is called martensitic phase transformation [1].

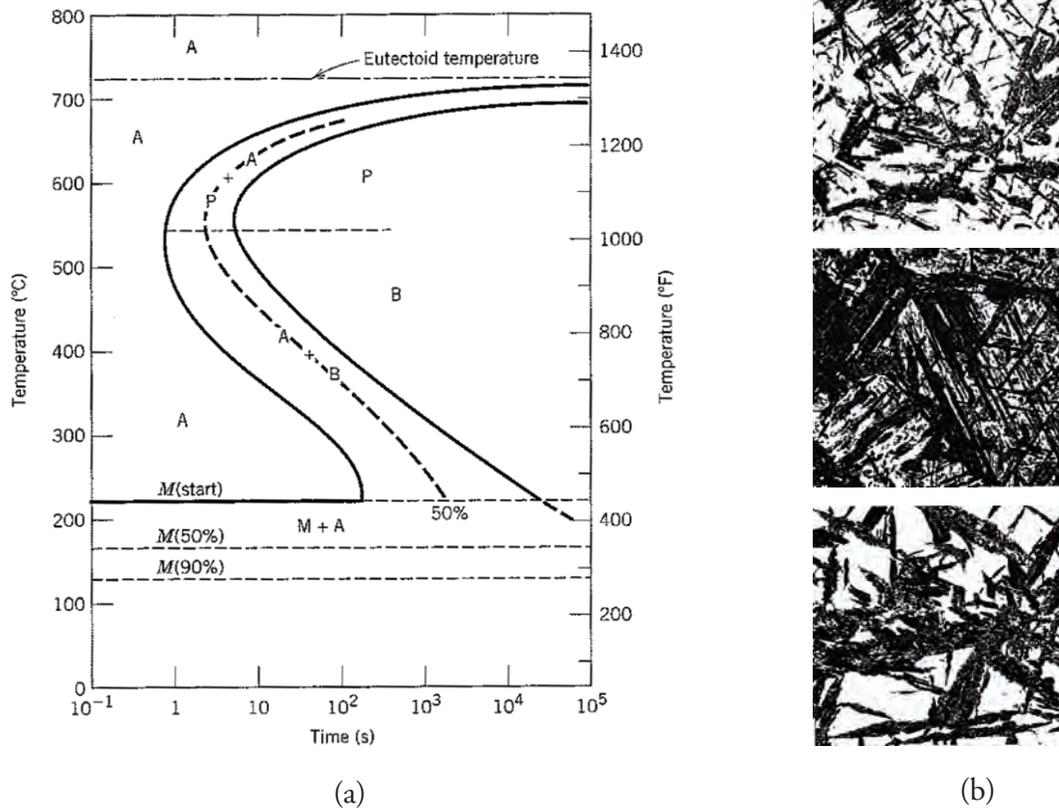


Fig. 1.6. (a) Time-Temperature-Transformation phase diagram of eutectoid steel and (b) steel microstructures formed at different cooling rates.

1.2. EXPERIMENTAL

Sample preparation requires polishing (Fig. 1.7(a)), observation with an optical microscope (Fig. 1.7(b)), heating in an environmental-control furnace (Fig. 1.7(c)), and quenching the heat-treated samples in oil or water.

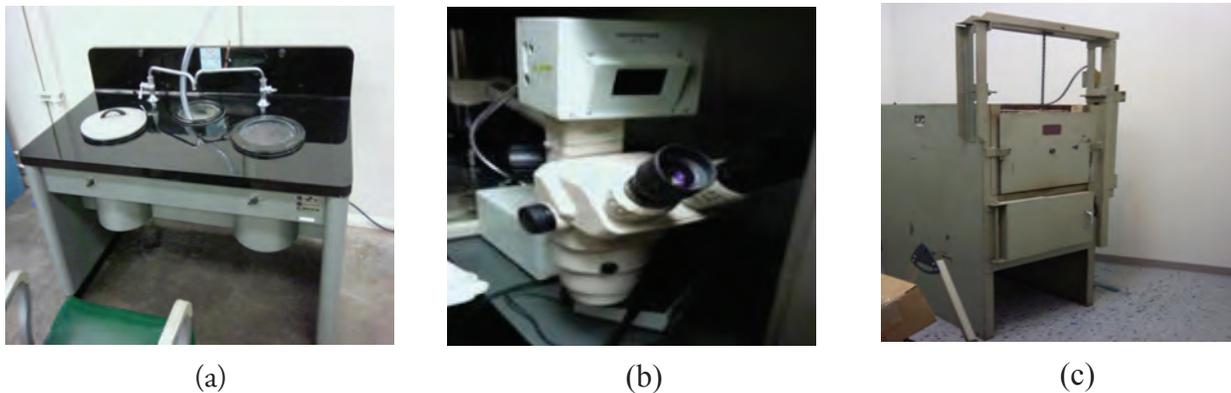


Fig. 1.7. (a) Polishing wheels, (b) optical microscope, and (c) heating furnace.

1.3. EXPERIMENTAL METHODOLOGY

1. Steel specimens consisting of AISI 1018 and AISI 1045 carbon steel will be polished sequentially with 320- and 600-grit SiC polishing paper. The better the steel sample is polished, the easier to observe the microstructure with the optical microscope.
2. Apply a chemical etchant (see details in Sect. 1.4.3), typically, 5 parts nitric acid and 100 parts alcohol, onto the polished steel surface to reveal the original microstructure.
3. Load the sample onto the microscope stage and observe the microstructure of the original (untreated) steel. Make a sketch of the expected microstructure and label the most characteristic features.
4. Heat the steel specimens to 850°C in the environmental furnace, hold the specimens at this temperature for 1 h, and then quench in oil (or water). Record the medium temperature and estimate the time for the specimen to reach the temperature of the quenching medium. Observe and describe the quenching process.
5. Repeat the previous steps for the other steel specimens.

Figure 1.8 shows AISI 1018 and AISI 1045 steel specimens before and after the above mentioned heating and oil-quenching processes.

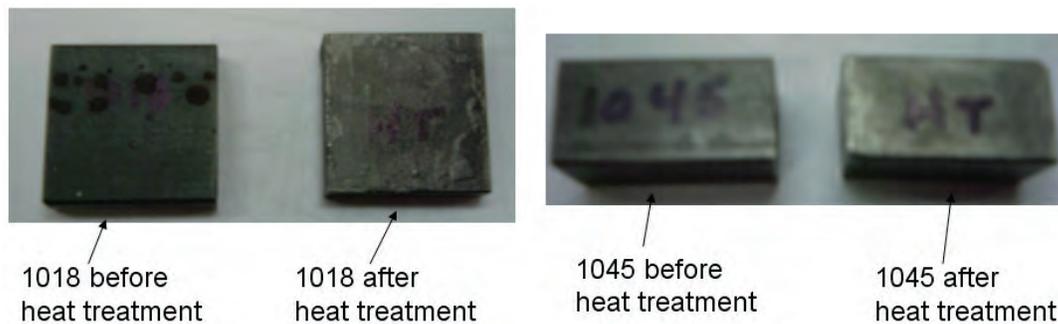


Fig. 1.8. Surface morphologies of steel specimens before and after heating at 850°C for 1 h in an environmental furnace and then quenching in oil.

1.4. OPTICAL MICROSCOPE OBSERVATION OF METALLURGICAL MICROSTRUCTURE

The major steps are: sample mounting, polishing, chemical etching and imaging.

1.4.1. Sample Mounting

To facilitate polishing, specimens should be sectioned to small pieces because small areas are easier to be polished flat than large areas. Epoxy mounting is highly suggested because the small specimen can be mounted into a large epoxy piece that is easy to hold by hand. The detailed procedure for sample mounting is as follow:

1. *Sample cutting.* This step makes specimens into small dimensions, probably 5 mm diameter range.
2. *Preparation grinding.* This step grinds away the roughness by the previous cutting. It does not require very high smoothness.
3. *Heat treatment.* This step will produce the martensite phase in the steel alloy.
4. *Pre-etching.* Martensite phase transformation requires quenching, and quenching may cause oxidation on the steel surface. This step etches away the oxide scale(s).

5. *Cleaning.* Water cleaning of the steel surface.
6. *Mold preparation.* Prepare the mold for epoxy and place the specimen inside the mold.
7. *Weigh epoxy.* Epoxy needs to be mixed by precise formula; this step prepares the epoxy materials.
8. *Mix epoxy.*
9. *Encase specimens.* Pour mixed epoxy into the mold.
10. *Furnace treatment of the epoxy.* This step cures the epoxy. The result will be one big piece that is easy to hold in hand.
11. *Mold release.* This step uses a liquid medium to remove the epoxy-bound specimen out of the mold.

1.4.2. Polishing

The detailed procedure for polishing is as follows:

1. *Belt grinder.* This is an electrical grinding facility that grinds away large asperities and surface contaminations by epoxy.
2. *Bench grinder.* This facility rolls the sand papers by electrical motor, with adjustable flow of lubricant. Usually four sand papers (240-, 320-, 400-, and 600-grit) are placed parallel on the bench grinder so it saves the time of changing sand paper. The epoxy-mounted specimens are progressively polished with finer sand paper.
3. *Additional bench grinder.* Because diamond paste polishing may not be effective after polishing with 600-grit sand paper, additional sand papers might have to be used to polish. Typically three sand papers (800-, 1000-, and 1500-grit) can be used sequentially.
4. *Diamond paste polishing.* After sand paper polishing, a diamond paste (typically 6 and 1 μm particle size) is used to further polish the specimen surface. Usually Plexiglas plates (typically 8 x 8 in²) holding the diamond paste are used as the flat surface for polishing. Since 1 μm is close to the wavelength of visible light, it is usually enough for the final mirror-polishing.

1.4.3. Chemical Etching

Nital and Picral are two typical etchants for alloy surface etching. Etching must be done immediately after polishing. Because nital (mixture of 2 wt.% of nitric acid in ethanol) can potentially explode, it must be stored with the cap loosely open, or with an inserted tube to let pressure release. The entire etching process must be done under a fume hood to maintain good air condition of the room and to prevent spill off. The typical etching steps are:

1. *Swab etching.* In this step, cotton floss sticks dipped with nital are used to swab the specimen surface.
2. *Water cleaning of specimen surface.*
3. *Alcohol cleaning of specimen surface.* This step is used to remove the water.
4. *Air drying.*

1.4.4. Imaging

Imaging by an optical microscope must be done immediately after chemical etching. The optical microscope has objective lens of 40x and an eye piece of 10x; therefore the magnification is around 400x. Since the magnification scale is not automatically set by the microscopes, a 1-mm long calibration scale can be placed under the microscope along with the specimen to label the dimension of the specimens. A digital camera is used to take digital images when the visual examination of the microstructure is satisfactory.

It may be necessary to go back and forth to polishing, etching, and imaging until a satisfactory image is obtained.

1.5. REFERENCES

- [1] Callister, W. D., *Materials Science and Engineering: An Introduction*, John Wiley, New York, 2003.
- [2] Chandler, H., *Heat Treater's Guide*, 2nd ed., ASM International, Metals Park, OH, 1995.
- [3] Van der Voort, G. F., *Atlas of Time-Temperature Diagrams*, ASM International, Metals Park, OH, 1991.

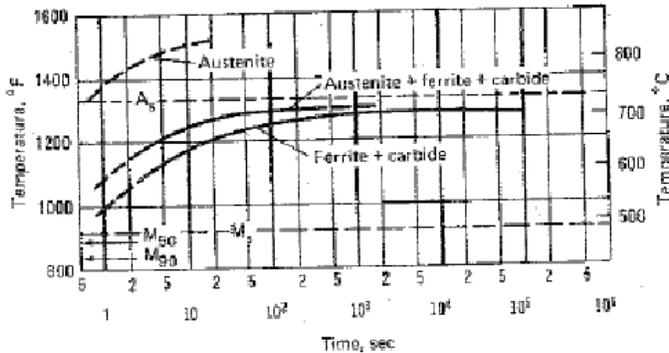
1.6. ASSIGNMENT

The main purpose of this lab assignment is to teach you how the microstructure of materials (in this case low-carbon (AISI 1018) and medium-carbon (AISI 1045) steel) can be altered by heat treating and then rapid cooling (quenching). This requires knowledge of phase transformations induced by temperature variation.

Your analysis and discussion should address and provide explanations to the following:

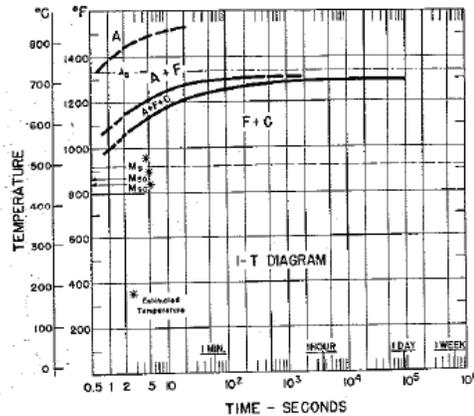
1. Determine whether the steel specimen can be classified as hypoeutectoid or hypereutectoid.
2. Discuss possible phases in the original (untreated) and treated steel specimens based on the equilibrium phase diagrams and the TTT diagrams.
3. Determine possible phases present in each steel microstructure before and after heat treating and quenching and justify your assignment.

1008 Isothermal Transformation Diagram



Heat Treater's Guide, 2nd ed

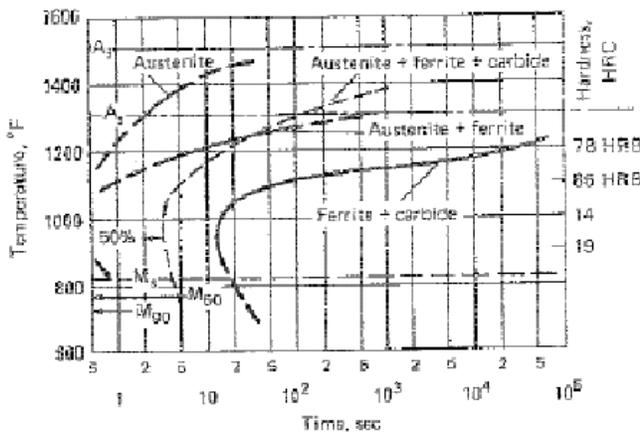
Reference [2]



Atlas of Time-Temperature Diagrams

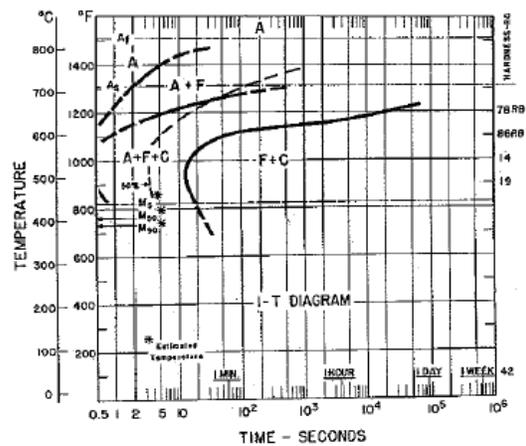
Reference [3]

1019 Isothermal Transformation Diagram



Heat Treater's Guide, 2nd ed

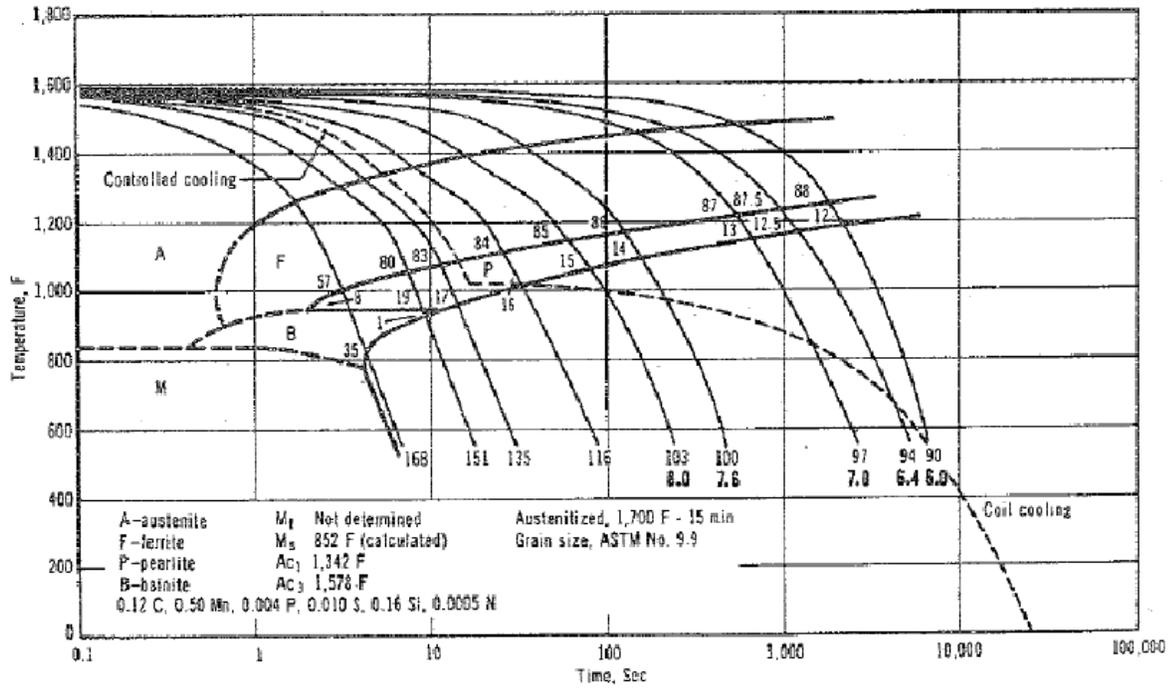
Reference [2]



Atlas of Time-Temperature Diagrams

Reference [3]

1010 Time-Temperature Diagram



Heat Treater's Guide, 2nd ed

Reference [2]