Two Processing-Structure-Property Laboratory Activities to Culminate a Course in Engineering Materials

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Abstract

Most engineering students are required to take a course which focuses on Engineering Materials. A common theme of these courses is that Processing affects Structure which in turn affects Properties which ultimately determine Performance. Two laboratory sessions have been developed which demonstrate this principle: TTT Diagram Evaluation and Evaluation of Strengthening Mechanisms. To complete the TTT Diagram Evaluation laboratory the students evaluate the hardness and microstructure of heat treated 1080 steel samples. Heat treatments include heating below the austenite transformation temperature, heating above the austenite transition temperature and then cooling at elevated temperatures, and tempering martensite at various temperatures. The students then compare their results to those predicted by either the TTT diagram or coarsening theory. The Evaluation of Strengthening Mechanisms laboratory assignment requires that the students evaluate grain/particle size reduction, second-phase particle strengthening, solid solution strengthening, and work hardening. This is done by subjecting copper, single phase brass, and two 10 series steel alloys to various heat treatments, including forming martensite. The students perform a tensile test to evaluate the yield strength and ductility and take micrographs of the alloys.

Introduction

Bloom's Taxonomy is key to the author's philosophy of engineering education[1]. Rather than emphasize the lower levels of learning: Knowledge, Comprehension, and Application, the author feels that lower level undergraduates should be required to perform at the Analysis level and upper level undergraduates at the Synthesis level. It is felt that this better reflects the maturity of the students. Engineering Materials is a core engineering course designed for the junior year. The course has three objectives:

1) Specify suitable materials for a given application using the relationship between mechanical properties, processing and material structure.

2) Describe how processing affects microstructure and thus material properties.

3) Communicate the above knowledge in written, oral and visual form.

The course is taught based on the chain shown in Figure 1. Students are told that processing affects structure, which in turn affects the properties of the material. Material selection for performance requires both specifying and understanding the material's properties. Therefore there are three segments to the course: Structure, Properties and Mechanical Properties.

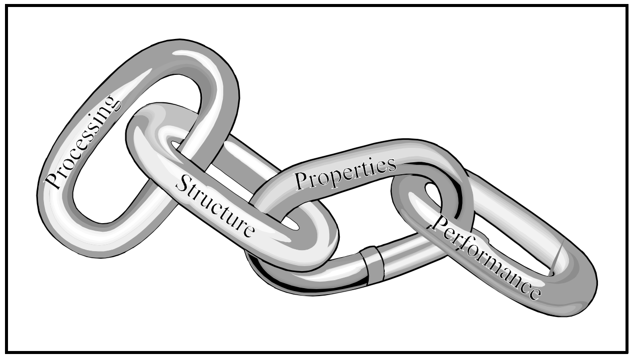

Figure 1: Materials Engineering Chain.

The laboratory is a key component to the course. Students are expected to perform real laboratory experiments. That is they need to present a hypothesis, justify and explain an experimental procedure, describe the results, and in the discussion analyze the results and assess the hypothesis. The class is divided into interactive class sessions, as described in earlier work[2] (36-55 students), and laboratory (12-15 students) sections[3,4]. All laboratory sessions are scheduled to occur between the two recitation classes. This way the background information is presented in the beginning of the week, the students perform the laboratory experiment, and the results and implications are discussed at the end of the week. The laboratory reports are collected as part of the weekly homework assignment, which often includes other questions about the laboratory, and are covered on the tests and final examination. Integrating the laboratory and "lecture" has been advocated by many authors as a means to improve engineering education[5,6]. Doing so is a demonstration of a quote "Tell, me and I'll forget, Show me and I'll remember, Involve me and I'll understand"[7].

Throughout the term students complete the following laboratory experiments

- Attempting to Correlate Heat Treatment Temperature to Hardness of Steel
- Attempting to Correlate Structure to Hardness of Steel (after the previous experiment proves difficult)
- Evaluating the Sn-Bi Phase Diagram based on both Structure and Phase Analysis[3]
- Evaluating Coarsening and Grain Growth in Sn-Bi Alloys[3]
- Evaluating the Validity of the TTT Diagram for Eutectoid Steel
- Evaluating the Effect of Various Strengthening Mechanisms in Metals

There are also three demonstrations which occur during the various lab periods. Students practice taking a micrograph early in the term. In the middle of the term students perform a simple tensile test on a series of materials. This is not considered an experiment, because all the students do is report their results demonstrating they can evaluate a stress strain curve and use spreadsheet software. During the last week of the term, students perform a tensile test on ABS and polypropylene at 25C, 50C and 110C to see the mechanical behavior of polymers as a function of temperature.

During the last two years two experiments were developed to further student's understanding of how processing effects structure and thus the properties of engineering materials: TTT Diagrams and Strengthening Mechanisms.

Experiment 1 - TTT Diagrams

Steel is one of the most versatile materials known, and its versatility was key to the industrial revolution. Most metals will become weaker, as a direct result of coarsening and/or grain growth, when heated at high temperature. Steel, however, is anomalous. When heated above 727ºC bcc-Fe transforms to fcc-Fe. When fcc-Fe is cooled below 727ºC the reverse is true. Controlling the transformation which occurs as fcc-Fe is cooled is key to controlling the strength and hardness of the steel. The TTT Diagram for eutectoid steel is shown in Figure 2. Note, when cooled at temperatures above 550ºC, pearlite (an equilibrium mixture of two phases - ferrite and cementite) will form, and the rate of transformation increases as temperature decreases. Bainite, a much finer equilibrium product will form at temperatures below 550ºC, but above 200ºC. Note, that the rate of transformation decreases as temperature decreases. When quenched to room temperature, martensite will form. Martensite is hard, brittle, and metastable. When heated above 300ºC, martensite will form tempered martensite which is a third equilibrium product.

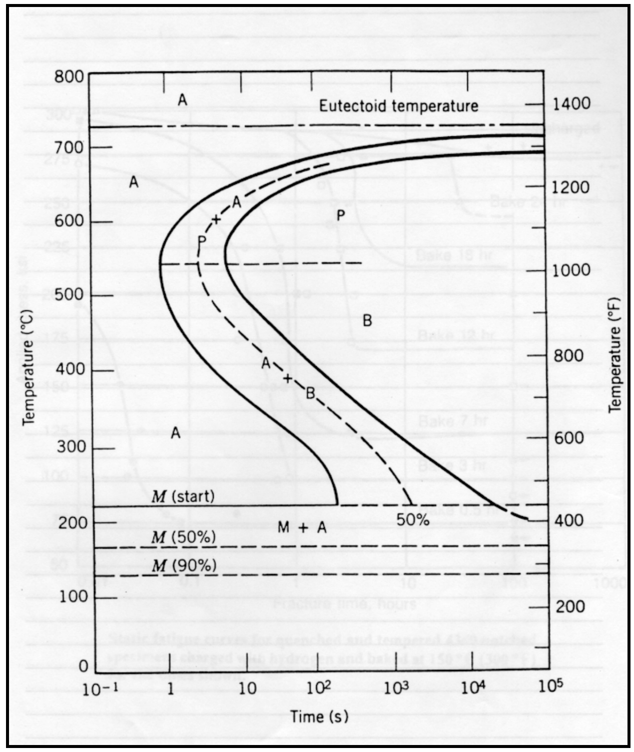

Figure 2: TTT Diagram for Eutectoid Steel

Pearlite (of the structures generated in the lab experiment) is the weakest, most ductile, and softest structure. Martensite is the hardest and most brittle. In this experiment students compare the properties of 1075 steel subjected to the following heat treatments.

- Untreated (as received from a donor - who did not specify prior treatment)

Treatments to Demonstrate Coarsening and Grain Growth

- Heated to 900F (480C) and held for 1-2 hrs and Quenched to Room Temperature
- Heated to 1100F (590C) and held for 1-2 hrs and Quenched to Room Temperature
- Heated to 1250F (680C) and held for 1-2 hrs and Quenched to Room Temperature

Treatments to Demonstrate Austenite Transformation

- Heated to 1650F (900C) held for over 2 hrs and Quenched to Room Temperature
- Heated to 1650F (900C) held for over 2 hrs, cooled to 1250F (680C) held for 1-2 hrs, and Quenched to Room Temperature
- Heated to 1650F (900C) held for over 2 hrs, cooled to 1100F (590C) held for 1-2 hrs, and Quenched to Room Temperature
- Heated to 1650F (900C) held for over 2 hrs, cooled to 900F (480C) held for 1-2 hrs, and Quenched to Room Temperature

Treatments to Demonstrate Tempering of Martensite

- Heated to 1650F (900C) held for over 2 hrs, Quenched to Room Temperature, heated to 1250F (680C) held for 1-2 hrs, and Quenched to Room Temperature
- Heated to 1650F (900C) held for over 2 hrs, Quenched to Room Temperature, heated to 1100F (590C) held for 1-2 hrs, and Quenched to Room Temperature
- Heated to 1650F (900C) held for over 2 hrs, Quenched to Room Temperature, heated to 900F (480C) held for 1-2 hrs, and Quenched to Room Temperature

All furnaces were saturated prior the beginning of the heat treatment. In those cases where 1650F samples were transferred to another furnace, the instructor quickly transferred the hot samples. Samples were quenched in large quench tanks (the samples were small less than 1 in^3) and were agitated. The importance of speed and agitation must be stressed. Speed is necessary to avoid cooling to a temperature where the pearlite transition is rapid. As shown in Figure 2, if the sample cools to 600C the complete transition will occur in less than 10 seconds. Agitation is necessary to break down the steam barrier which forms around the sample.

Students then section, mount, grind and polish their samples. Typically the last polishing step uses a 6 micron diamond paste. Samples are then etched in a 3% Nital solution. Students use a computer based image analysis system to take micrographs.

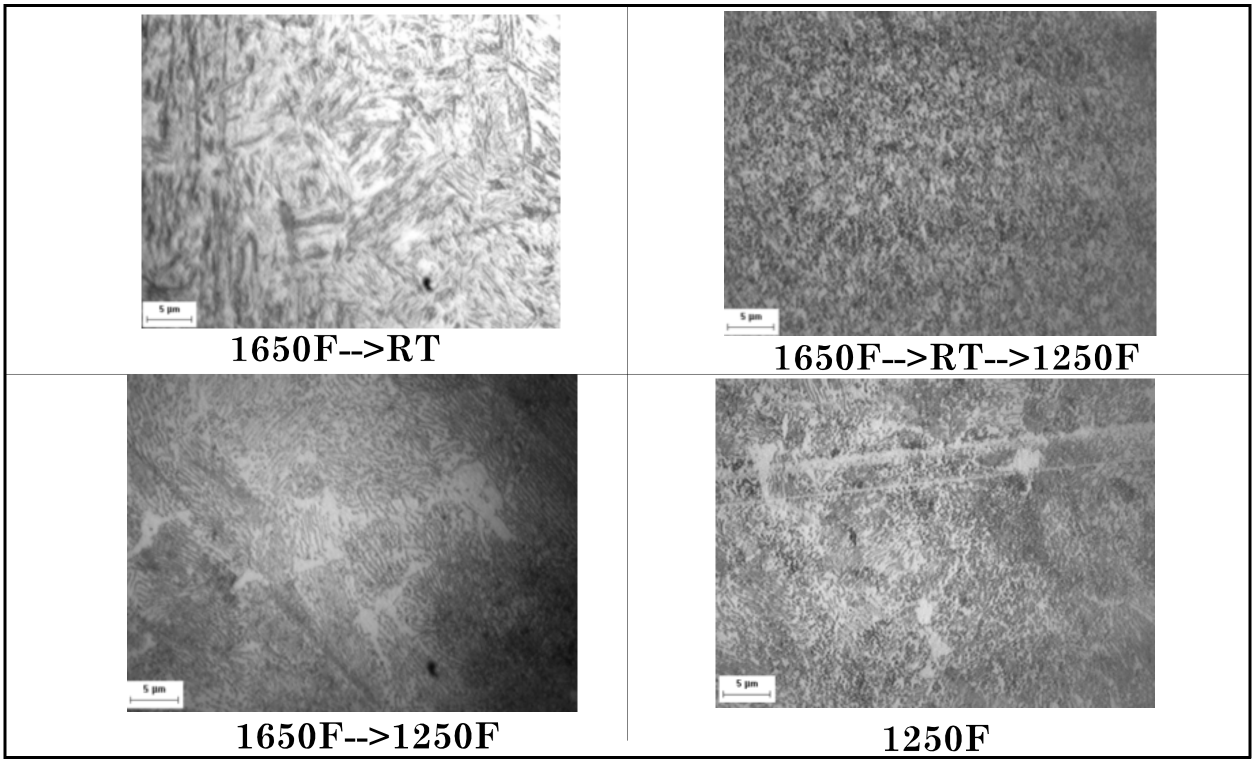

Figure 3: Microstructures of 1075 Steel Subjected to Various Heat Treatments

Figure 3 shows the microstructures of four of the steel samples. Martensite is formed through the 1650F-RT (Room Temperature) treatment, tempered martensite is formed through the 1650F-RT-1250F treatment, coarse pearlite is formed through the 1650F-1250F heat treatment, and coarsening is evident when steel is annealed. Students then perform Rockwell A Hardness tests on the samples. This scale was chosen as several of the samples have hardness values which overlap the Rockwell B and Rockwell C Scales.

To complete the laboratory report, the students use the data collected by the class as a whole. Every student performs a hardness test and prepares a sample for microstructural analysis. It is here that they must synthesize the knowledge they have learned. In the introduction students are required to explain the TTT diagram. They are expected to communicate the following to the instructor that pearlite has a coarse structure because it forms at austenite grain boundaries, that it forms at the grain boundaries because of the high temperature, and that because of this its structure it is the softest of the materials. They are expected to do this for all structures. In the discussion they are expected to compare the structure which what would be expected from the TTT diagram with that observed. They are responsible for explaining any discrepancies. Retention of this knowledge is assessed on a subsequent test, where given a TTT diagram and a series of heat treatments (including simple coarsening), they must predict the hardness various steel samples.

Experiment 2 - Strengthening Mechanisms

The final experiment in the course is used to “tie everything together”. Students examine the effect of four possible strengthening mechanisms: second phase particle strengthening, solid solution strengthening, work hardening, and particle/grain refinement. Particle/grain refinement is tested “in reverse” as they compare annealed samples to unannealed samples. As in the TTT Diagram experiment, students each student tests one sample, in this case a tensile test, and prepares a sample for microstructural analysis. Below is a description of each part of the experiment.

- Grain / particle size reduction was evaluated by comparing the properties of copper, brass and steel at various temperatures. Copper, steel and brass were annealed at 1000F (540C), and/or 1200F (650C) for two hours and then quenched to room temperature. Steel was also annealed at 1650F (900C) for two hours and quenched to room temperature.
- Work hardening was evaluated by comparing the properties of annealed copper and/or brass with copper and/or brass which has been annealed at 1200F (650C) and then work hardened. The work hardened samples were made by interrupting the tensile test.
- Solid solution strengthening was evaluated by comparing the properties of copper and brass.
- Second phase particle strengthening was evaluated by two of the following grades of steel: 1018 (Fe-0.18 w/o C), and 1050 (Fe-0.5w/oC) steels.

On the following page are tensile test curves from two parts of the experiment: work hardening and heat treatment temperature effects on mechanical properties. Note the anomalous behavior of steel is illustrated.

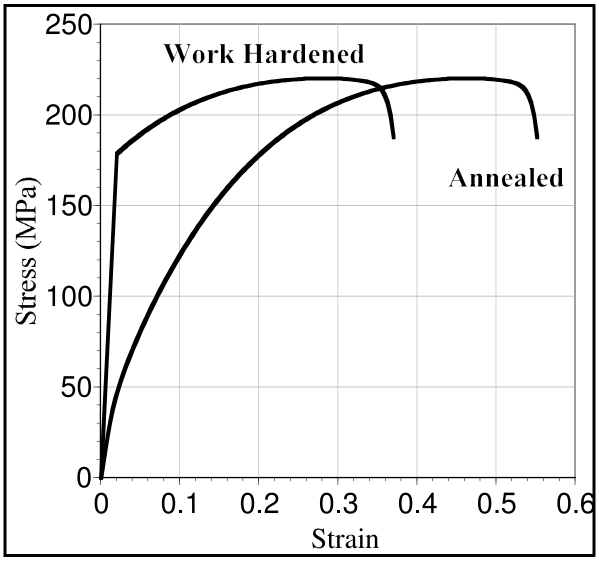

Figure 4: Stress-Strain Behavior of Copper Annealed at 1200F and work hardened.

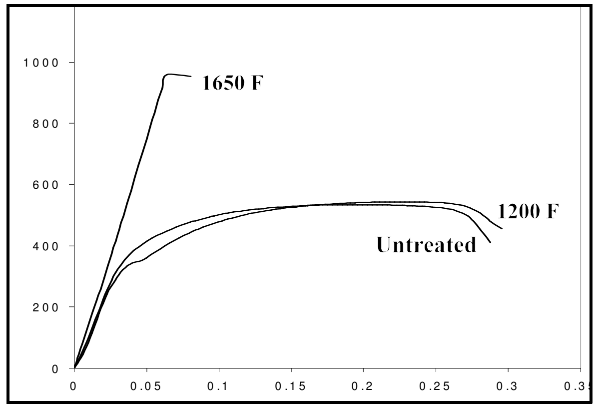

Figure 5: Stress Strain Behavior of 1050 Steel Untreated, Annealed at 1200F, and Annealed at 1650F

Figure 4 shows the effect of work hardening. In this case the tensile test was interrupted at a strain of about 25% and then a new tensile test was performed as if the bar were as received. Note, that yield strength of the work hardened specimen is much higher than the fully annealed specimen. Figure 5 shows the affect that annealing temperature has on the strength and ductility of 1050 steel. Note the anomalous nature of steel is demonstrated. Heat treating at 1200F made the material slightly weaker and more ductile, while heat treating at 1650F and quenching made the material stronger and more brittle.

Discussion

These experiments when fully integrated into the course have had a positive impact on the students. As everyone is aware the accreditation requirements for engineering schools require outcomes assessment where, each school seeking accreditation must establish and document a system of on-going evaluation[8]. To evaluate the effectiveness of this course, course topics were matched to course objectives. Information regarding how effective each course topic was learned by the students was be collected from 1) recorded performance on test questions, 2) detailed questions on the course evaluations addressing specific course topics, and 3) student comments. Recognizing that there is no formula for assessing the effectiveness of a learning experience these data were collected using an outline based on a published assessment guide[9], and revised so that a three to five page summary will be prepared for review[10]. This summary and supporting documentation is reviewed by the department chair or designee(s) as part of the annual evaluation and promotion / tenure documentation.

Results from the last academic year were positive. The strengthening experiment was a major success. Grades showed that on average, 70-80% of the students could determine which material would be stronger and explain why. For example, they knew that work hardening strengthened a material, although optical microscopy would shed little light as to why. The behavior of steel was well understood. Typically the average rating by students for this course topic was 2.8-3.1/4.0, however between 70 and 80% of the students rated the coverage of this topic as good or better and less than 10% (usually less than 5%) rated this as less than acceptable. About 5% of the students chose to comment positively on course evaluations, while none made negative comments. The TTT diagram experiment also had a positive impact. On average 2/3 of the students rated the effectiveness of that this topic was presented (which also included phase diagrams and diffusion on the questionnaire) as being taught good or better, and between 8 and 10% as less than acceptable. The average student course evaluation of this topic was 2.6-2.9/4.0. Only 2 students during the year commented that TTT Diagrams needed to be better taught, while 5 chose to mention they were taught well. Performance on the test and final examination indicate that the students could predict the strength of a steel alloy based on the TTT diagram. They did have difficulty understanding why the structure formed. It also must be noted that the TTT diagram experiment preceded and helped prepare the students for the Strengthening Mechanism Experiment.

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