AC 2011-1147: TEACHING DEMO TO REINFORCE HOW MECHANICAL PROPERTIES CHANGE DUE TO HEAT TREATMENT PROCESSES

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Teaching Demo to Reinforce how Mechanical Properties Change Due to Heat Treatment Processes

Abstract

Lecture coupled with some hands on demonstration is a powerful teaching strategy for engineering students. This style of teaching was incorporated into an engineering materials selection course. Students realize that changing material properties play an important role in understanding why materials are selected for different design specifications. Engineering students take courses in mechanics of material, machine design, finite element analysis and capstone senior projects. These courses require students to call out and specify the best and least expensive material according to some type of chemical, physical or mechanical loading conditions. Students should understand the way a material behaves in service depends upon its alloy composition, crystalline structure, manufacturing process and heat treat condition.

This paper is written after developing a hands-on material lab that teaches engineering students how heat treatment processes affect material properties. Its main focus is with AISI 4140 alloy steel, however, other carbon and alloy steels can be used and explored by the same procedure outlined in the lab handout. The first part of the lab requires students to set up a heat treat furnace. They quench harden and temper thirteen charpy specimens. The range in hardness are from dead soft to its maximum hardness that the material can acquire. Hardness and toughness values are measured and the data are plotted to generate material behavioral curves. From the Brinell hardness number the ultimate tensile strength is estimated and plotted against hardness and toughness values. A series of design questions in the lab handout helps reinforce the theory taught in the class room to this hands-on learning process.

Why this Teaching Method?

Teaching materials selection can often be unimaginative and uneventful for students. They experience a lot of reading, memorization of processes and definitions in this class. A different approach developed from an ABET criteria for assessment was implemented as a hands-on lab to determine mechanical properties. The ABET assessment tool was “The Course Level Loop Assessment Action” shown in figure 1. This tool is intended to capture and document teaching and learning improvements based on informal assessment of ongoing courses. The assessment driving a particular action may be generated by student feedback, instructor generated, peer generated, etc. Problems are noted on the form and improvement actions are documented, implemented and then assessed. This closed loop assessment tool shown in figure 1 was implemented for this material selection course and prompted two actions for this paper. The first was to engage students in the learning process of mechanical properties by having them set up and break a bunch of charpy specimens of different heat treatments. Second, students lack completeness in generating graphs of lab data. This paper puts a strong emphasis on improving such graphing skills by having the students construct a series of material behavior graphs from the data and other equations implemented in the lab write up.

ABET Course Level Loop Assessment Action 2009				
Course: MET 3150 Materials Selection and Heat Treatment		Faculty Responsible for Survey and Action Items: Prof. Magda	Faculty Responsible for Proposed Future Action: Prof. Magda	Faculty Responsible for Implemented Action: Prof. Magda
Semester: Spring				
	Source of Information	Item for which action is implemented or proposed	Proposed Future action on Item	Implemented Action on Item
1	Student Questionnaire	Would like to learn more through hands-on laboratory experiences that complements the theory taught in class	Develop additional lab work to measure the changes in mechanical properties due to heat treatment and tempering processes of 4140 steel	Implement a testing lab that students conduct that will measure hardness and toughness of various heat treat conditions of 4140 steel. Have students plot six different material behavior graphs from the hardness and toughness data and discuss the relationships between mechanical properties
2	Course Evaluations	More time needed to complete the exams	Reduce the number of problems on the exams	Add additional exam to compensate for the reduction of exam problems
3	Prof. Magda Observations	1. Students like testing and breaking test specimens. How can we engage this as a teaching/learning opportunity? 2. Students submit poor incomplete graphs of experimental data	1. Develop a student driven hands-on lab 2. Develop a testing lab where students graph materials behavior curves to show the relationships between mechanical properties and tempering temperatures	1. Implement a new lab where the students can set up and break charpy test specimens for the spring 2010 semester 2. Implement lab with a strong emphasis on graphing data to improve students graphing skills

Figure 1. ABET Course Level Loop Assessment Action.

Introduction

The versatility of a steel is, to a large measure, attributable to its response to a variety of thermal treatments. This greatly broadens the spectrum of properties beyond those attainable through composition and processing controls in the as-rolled condition. Treatments fall into two categories: first, those which increase strength, hardness, and toughness by quenching and tempering; secondly, those which decrease hardness and promote uniformity by slow cooling from above the transformation range or by prolonged heating within or below the transformation range followed by slow cooling. The first category can involve through hardening as previously mentioned, or a variety of special treatments intended to enhance surface hardness to a controlled depth. The second category encompasses normalizing and various machinability, toughness or cold forming characteristics, or to relieve stresses and restore ductility after processing involving some form of cold deformation.

Alloy steels are extensively used in many design applications because of their high strength and toughness properties. Other materials like, tool steels, ceramics and maraging steels are some examples of materials that can exhibit very high strength but very low ductility. The impact energy on a charpy test would be well below 15 ft-lbs of energy classifying them as a brittle material. These materials have very little to no plastic region on a stress strain diagram. Tool steels and high strength alloy steels can even fracture well below the ultimate tensile strength of the material. This is caused by stress concentrations and the lack of ductility that does not allow the state of stress to relax within the geometric discontinuities.

Ductility is a measure of plastic deformation and is a required material property for joining, extruding, swedging, drawing and forging operations. Introducing the metal to some mechanical cold working manufacturing process can easily alter the material properties of strength, hardness and toughness to some degree by changing dislocation density and grain size. However, applying a thermal heat treatment process to an alloy steel will affect the structure and phase of the material. This changed microstructure also produces a dramatic increase or decrease in mechanical properties for design specifications.

Students should have a good understanding of the Iron-carbon equilibrium diagram and a typical time temperature transformation (TTT) diagram for structure and phase changing of steel. As students work through this laboratory exercise, they will plot material behavioral curves of mechanical properties to reinforce the theory taught in class.

Structure and Phases of Steel

There are different phases an alloy steel can exhibit through a heating and cooling process. If austenite is very rapidly cooled, diffusion controlled transformation to ferrite and pearlite may not be possible. Instead, the austenite changes its crystal structure by a diffusionless shearing mechanism that moves blocks of atoms.¹ The carbon originally dissolved in the solid solution of austenite, is now trapped in a ferritic structure. Since ferrite has an extremely low solubility of carbon, its crystal structure becomes distorted to accommodate the presence of the trapped carbon, resulting in a volume expansion. This new microstructure is called martensite.

Martensite is no longer a true body-centered cubic phase, but rather a body-centered tetragonal (bct) structure. The extreme distortion imposed by the carbon atoms is said to account for the substantially higher hardness and strength of this microstructure. The temperature at which austenite starts to transform to martensite is termed the M_s temperature and the temperature at which it is finished is called the M_f temperature. The maximum rate of cooling required to produce 100% martensite is called the critical cooling rate. A typical time temperature transformation (TTT) diagram showing the start and finish of martensite is shown in figure 2.

Figure 2. Time temperature transformation (TTT) diagram. ²

It is also observed that steels of higher carbon content being more distorted, would produce martensite of greater hardness, and this is in fact is true. However, not all martensitic structures are created equal, with their hardness, toughness, tensile strength, wear resistance and other mechanical properties controlled by the steel's carbon content. Martensite is the product of cooling austenite at a rate equal to or faster than the critical cooling rate. The diagram above shows this as the cooling line being to the left of the knee of the austenite + pearlite curve. In order to produce martensite, one has to initially start with austenite. Martensite then starts to form on rapid cooling at the M_s temperature. The M_s temperature decreases sharply with increasing carbon content in steels. All other alloying elements, such as Cr, Ni, Mn, Mo, lower the M_s , except for Co which raises the M_s . A significant effect of low M_s temperatures is incomplete austenite to martensite transformation at room temperature. Therefore, as quenched martensitic structures may retain austenite as part of its room temperature microstructure. If left untransformed, the retained austenite at room temperature becomes an accident waiting to

happen. This typically requires quenching to sub zero temperatures to fully transform all of the remaining austenite to martensite.

Although martensite can be a very hard, wear resistant, strong material, it lacks ductility, toughness and in all but low-carbon steels it is extremely brittle. Consequently, martensite must be reheated to a specific tempering temperature for two hours to enable parts to be used for industrial purposes. Heat treatment reduces the internal strain in the bct structure, thereby increasing ductility and toughness, at some expense to hardness, wear resistance and strength.

Tempered Martensite

Typically all hardening processes are followed by a tempering heat treatment process . A steel through-hardened to a martensitic structure is not a satisfactory engineering material for most applications unless your using it as a substitute for a tool steel. Despite its potential strength, it lacks ductility and toughness, often to the point where its full strength cannot even be measured since failure is so easily initiated. In order to develop ductility and toughness, the quenched steel is further treated by tempering.

Martensite is not a stable constituent, and on heating it will decompose to its stable products, ferrite and cementite. The extent of this decomposition will depend upon tempering temperature and time at temperature. At high tempering temperatures and/or long periods of time, decomposition of martensite can be so complete that it approaches the mechanical properties of ferrite (soft, ductile, low strength and hardness). At low tempering temperatures and/or short tempering times, decomposition is minimal and the martensite remains hard and strong with slight increases in ductility and toughness. Thus, the appropriate choice of tempering temperature and time at temperature is required to achieve the specified mechanical properties necessary for the intended application.

In tempering fully quenched martensitic steels, it should be cautioned that a loss in ductility may result from prolonged heating between 500 and 650°F. Between these temperatures, the notch ductility of the steel (assessed by charpy testing) is reduced. This phenomenon is called temper embrittlement or blue brittleness. This behavior will be demonstrated in the lab assignment.

The effect of all alloying elements is to reduce the rate at which martensite will temper. Thus, at a given tempering temperature, and for a given time, the alloy steel will show a greater hardness than the unalloyed steel. The design of steels and cooling conditions to produce required amounts of martensite are the subject of the technology referred to as hardenability. By alloying a steel you can easily shift the knee of the curve in figure 2 to the right therefore allowing more time for austenite to transform to martensite. This time is critical especially when large mass components need through hardness to achieve high strength properties. In this paper the material selected was AISI 4140 alloy steel. The hardening, quenching and tempering processes to form tempered martensite is summarized in the next three section as it applies to critical heat treatment procedures. This 4140 alloy material along with its size of specimen will result in excellent hardenability to achieve a wide range of mechanical properties for this lab.

Pre-Lab the Hardening Process

The first step in this process is to heat the steel to the correct temperature for quenching. All alloy steels have a critical range, and it is necessary to heat the steel above this critical temperature range in order to be able to fix by quenching, the changes desired. (All companies making alloy steels furnish the correct quenching temperature for their steels.) Care must be exercised in the rate of heating. When the steel is placed in a furnace, the temperature of the surface of the steel is first raised and the heat then travels through the steel by conduction toward the center. This process continues until the entire mass has reached the same temperature as the furnace itself. When the steel is first heated, it expands and if a cold piece of steel is placed in a hot furnace the surface expands more rapidly than the core. The surface will then have a tendency to pull away from the center thus inducing internal stress. In soft steels, this condition is not too important as the steel is sufficiently ductile to accommodate itself to this expansion; however, the harder steels are much more susceptible to injury due to rapid heating, and, therefore, should be pre-heated before being placed in a hot furnace. Pre-heating is not actually necessary for small sections if the quenching temperature is below 1600 degrees F., however, if a material has large or heavy and light sections which are adjacent, it should be preheated to avoid excessive temperature gradients that could cause warping or cracking during heating. The average steel can be heated at the rate of five minutes per 1/8" of thickness. After the steel is up to temperature, it should be allowed to soak for at least five minutes per inch of diameter or thickness after which it is ready to be quenched. The furnace temperature should never be hotter than the quenching temperature. In other words, if the quenching temperature is 1500 degrees the furnace should be held at that temperature and the steel allowed to reach this temperature. A furnace with automatic temperature is recommended for precision work.

Quenching Process

More steel is ruined in this process than any other phase of heat treating. The purpose of quenching steel is to fix in it some of the changes which have been caused by heating the steel above the critical range. Quenching at the correct temperature results in an increase in hardness and tensile strength. All alloy steels and tool steels are made for a definite quenching medium for best results and the steel company will specify which medium is to be used - air, oil, or water. When using liquid baths, sufficient quenching fluid must be used so that the liquid will not get too hot for effective quenching. Quenching should not be continued beyond the point necessary to produce the required hardness penetration. In other words, the sooner a part can be removed from the quenching bath and the drawing or tempering operation performed, the less will be the danger of quenching cracks. Generally speaking, the steel should be removed from the quench when it is approximately 150 degrees Fahrenheit and then be allowed to cool to room temperature after which it should be immediately placed in the tempering oven. Approximately one gallon of oil or water should be provided for every pound of steel quenched per hour. If the bath is in constant use, it will be necessary to provide some means of removing the heat by circulating the quenching medium through cooling coils. Rapid liquid quenching will produce a greater difference in hardness between the surface and the center of any large section. Consequently, in large sections, more quenching stresses will be developed. In general, it is not good practice to use a drastic quench to secure surface hardness on large sections. The shape of the part being quenched has a definite relation to the type of quenching medium best suited for

the job. When the part consists of thick and thin sections, a drastic quench will harden the thin section before the thick part has had a chance to cool. This premature cooling of one section will produce uneven contraction and stresses which frequently results in cracking. Surface finish is a factor not to be overlooked in quenching. A smooth surface will cool more rapidly in quenching than a surface which is rough machined. This is due to the fact that steam or gas bubbles will adhere more tightly to a rough surface, thus preventing the normal removal of heat during the quench. It is important to circulate the quenching medium rapidly or agitate the parts being quenched so as to prevent this adherence of gas or steam bubbles to the surface of the steel if the maximum quenching effect is to be obtained.

Drawing or Tempering Process

When the steel is fully hardened, it is in a highly stressed condition and is too hard and brittle for applications. It is, therefore, necessary to relieve this stressed condition, increase the toughness and ductility, and still retain sufficient hardness and strength. This change can only be made by the application of heat and this process is known as drawing or tempering. This consists of reheating the quenched steel sufficiently to transform the hard martensite into other softer tempered martensite. Different degrees of hardness can be developed in the steel by utilizing different drawing temperature. The higher the drawing temperature, the softer the steel becomes. An oven with automatic temperature control is recommended for precision work. Be sure to bring the furnace and tool up to temperature together. Do not put cold steel in a hot oven. It is very important that this operation be done just as soon as possible after the quench in order to promptly relieve the quenching stresses. In cooling steel after the draw, no change in hardness or ductility will take place whether the steel is cooled rapidly or slowly; however, it is advisable to allow the steel to cool normally in the air rather than quench it because a sudden quench might set up shrinking stresses. Time is an important element in drawing. More complete stress relief is secured by a longer soak at the drawing temperature. Without increasing the draw temperature, greater toughness is also obtained with a long draw rather than a short one. Double tempering is a wise precaution. It is a corrective treatment which the writer recommends. It can do no harm and may do a lot of good. All steels have a recommended draw temperature for a definite hardness; however, time is a very important factor. The time generally given by the steel manufacturer means time at temperature; therefore, in order to get the correct total time in the oven, it is necessary to add the time required for the tool to reach oven temperature. Unsatisfactory hardening of a steel is most likely caused by:

1. Failure to remove (machine off) sufficient surface of hot rolled bar before hardening.
2. Failure to heat to high enough temperature.
3. Failure to quench fast enough.
4. Overheated (Too high above critical range).
5. Decarburized surface.
6. Contaminated water or oil.
7. Use of wrong steel.
8. Re-worked tools must be thoroughly annealed before hardening.

Materials Laboratory

Material Behavior Testing

- Objective** To determine the effect of different heat treatment conditions have on mechanical properties of AISI 4140 steel. The properties tested and measured are hardness and toughness. From these values you should be able to calculate the ultimate tensile strength and fatigue strength of the alloy steel in its heat treat condition.
- Background** Study and review the theory and procedures for hardness and charpy testing. Also review the section in your materials book on the thermal processes of hardening and tempering. Have a good understanding of metallurgical phases and microstructure pertaining to mechanical properties of alloy steels.
- Material** AISI 4140 steel
- Procedure** This is a group lab where every student will contribute testing data to fill in the test matrix attached to this sheet. The lab group are given 13 charpy test specimens shown in figure 3, in various hardened and temper conditions. These charpy specimens were quench hardened and tempered over a tempering range from 100 °F to 1300 °F. Make sure you develop a numbering system for the specimens to keep track of them as you conduct the hardness and impact tests. The first step is to measure the Brinell hardness in at least two or three locations per specimen and record the average value in the test matrix. Then its time to bust the specimens in-half. Set up and calibrate the charpy impact test machine shown in figure 4 and figure 5. Each student will then conduct and measure the impact energy or toughness values for the thirteen specimens. These toughness values are then entered into the test matrix according to your numbering system. Fill in the rest of the matrix by using the equations below. Then enter the temperatures that correspond to the data you measured and generated. These temperatures are incremented by 100 degrees F.
- Plot the data of hardness vs. tempering temperature, tensile strength vs. hardness, toughness vs. hardness, fatigue strength vs. tensile strength, tensile strength vs. tempering temperature and toughness vs. tempering temperature.
- Report** Follow the lab format procedure
- Equations** An industry standard for the approximation of the ultimate tensile strength from the Brinell number is $S_{ut} \text{ Ksi} = .5(\text{Brinell \#})$ for carbon and alloy steels only. ³ Also, the material fatigue strength can be calculated as $S_e = .5(S_{ut})$

ASTM type A Charpy V-notch specimen
Material AISI 4140
Dimensions in inches

Figure 3. Test coupon geometry for notch bar impact testing. ⁴

Figure 4. ASTM Charpy test specimen positioned in the Charpy test fixture.

Figure 5. Charpy impact test machine.

Lab Data Test Matrix Sheet

Material 4140 Specimen #	Temper °F	Average Brinell # HB	Tensile S_{ut} Ksi .5 x HB	Fatigue Ksi .5 x S_{ut}	Toughness ft x lb
1	100	630	315	157.5	7
2	200	627	313.5	156.7	20
3	300	590	289	144.5	21.5
4	400	556	267	133.5	19
5	500	534	247.5	123.5	17.4
6	600	495	230.5	115.2	16
7	700	461	214.5	107.2	15.5
8	800	429	194	97	19.5
9	900	388	172.5	82.2	40
10	1000	341	155.5	77.7	60
11	1100	311	138.5	69.2	78
12	1200	277	117.5	58.7	88
13	1300	225	112.5	56.2	90

Lab Results

Lab questions

1. Explain the relationship between hardness and toughness? Give two examples of a design where you would choose one over the other as the main material selection factor?
2. Which specimens have fracture characteristics of a cleavage failure?
3. Comparing the fracture surfaces of the 4140 steel what geometry characteristics can you summarize on the ductility, formability and workability of the material?
4. Your designing a roller coaster axle made of 4140 steel. The coaster speeds are up to 80 mph with inverted loops. Dynamic loads are 2000 lb with a cantilever distance of four inches. Determine what the diameter, hardness and ultimate tensile strength should be for the material? Explain why?

Assessment and Evaluation of Student Learning

Performance-based assessment method was implemented to evaluate this paper as a teaching tool for student learning. This method consists of a blind student survey, grading of lab reports, and oral communication within the lab. The blind student survey consists of the following questions that the students fill out after the lab assignment was submitted.

Blind Student Survey

Key (SA) strongly agree, (A) moderately agree, (D) disagree, (SD) strongly disagree, (U) unsure

1. I learn more when other teaching methods are used.	(SA)	(A)	(D)	(SD)	(U)
2. I would take another course that has hands on labs.	(SA)	(A)	(D)	(SD)	(U)
3. The lab material was to difficult to comprehend.	(SA)	(A)	(D)	(SD)	(U)
4. It was easy to remain attentive in the lab.	(SA)	(A)	(D)	(SD)	(U)
5. Not much learning was gained by this lab.	(SA)	(A)	(D)	(SD)	(U)
6. Some things in the lab were not explained very well.	(SA)	(A)	(D)	(SD)	(U)
7. I would have preferred another method of teaching.	(SA)	(A)	(D)	(SD)	(U)
8. Oral discussions in the lab facilitated your learning.	(SA)	(A)	(D)	(SD)	(U)
9. I enjoyed the group dynamics learning in a team environment.	(SA)	(A)	(D)	(SD)	(U)
10. Overall this lab was a good additional to the course.	(SA)	(A)	(D)	(SD)	(U)

The sample size for this assessment survey was 42 students. Each statement one through ten is weighted as 100%. The following assessment data shows the evaluation of the blind student survey. This assessment data indicates a positive effect on student learning.

1.	(SA) 11%	(A) 17%	(D) 39%	(SD) 31%	(U) 2%
2.	(SA) 41%	(A) 29%	(D) 13%	(SD) 8%	(U) 9%
3.	(SA) 4%	(A) 6%	(D) 19%	(SD) 68%	(U) 3%
4.	(SA) 72%	(A) 21%	(D) 0%	(SD) 7%	(U) 0%
5.	(SA) 3%	(A) 4%	(D) 42%	(SD) 51%	(U) 0%
6.	(SA) 4%	(A) 0%	(D) 12%	(SD) 78%	(U) 6%
7.	(SA) 2%	(A) 9%	(D) 25%	(SD) 53%	(U) 11%
8.	(SA) 41%	(A) 47%	(D) 7%	(SD) 0%	(U) 5%
9.	(SA) 15%	(A) 25%	(D) 31%	(SD) 24%	(U) 5%
10.	(SA) 47%	(A) 33%	(D) 9%	(SD) 7%	(U) 4%

Hands-on learning was also assessed and evaluated during the lab by having random students tell me what approximate values of hardness, toughness or tensile strength should expect during the testing sequence. If the student gave me an answer that was correct, I would continue to ask more detailed questions as a following up. With wrong answers or just guesses, I would give the student some clues or a scenario that would help the student figure out the answer for them. As the lab goes on, I tell the students that at the end of the lab I will ask one more time for someone to tell me what were the objectives learned in the lab. This oral communication within the lab between a professor and students fostered group dynamics in learning.

Summary

The ABET Course Level Loop Assessment Action was a success for the teaching and learning outcomes in this material selection course. This hands-on lab has been implemented into the MET materials class to facilitate the theory taught in the classroom. The tools for assessment of learning are the blind student surveys, oral discussions as the lab is being conducted, grading of lab reports and direct opinion from students commenting on how they understand and learn through practical experiences. In the classroom there have been an increase enthusiasm discussing materials and their properties. Finally compared with previous semesters the students understand the relationships between mechanical properties and they enjoy breaking specimens in the lab. The extensive graphing of the data improved their skills set not only in this class but other engineering technology classes where they are required to present graphical data. The element of learning material properties by a hands on application testing labs conducted by students was a tremendous success in this material's selection class. Overall this lab addition has been a successful motivational learning tool for students.

References

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