TEACHER INSTRUCTIONS

Thermal Processing of Bobby Pins

Objective: To show the difference that processing, especially thermal processing, can have on the properties of a material.

Background Information: A material can possess a variety of different mechanical properties such as strength, stiffness, plasticity, elasticity, and deflection. Deflection is the amount of displacement experienced by a material when placed under a load. This property is of great importance in building construction, and building codes often specify a maximum allowable deflection, generally as a fraction of the length of the beam. A material's mechanical properties are dependent on the material's microstructure, including the phases present, the number and arrangement of dislocations, and the grain size and shape.

Thermal processing is used to change the crystal structure, defect structure (dislocations), and/or grain structure of a material. Annealing is a process used to weaken metals, such as steel, to make them easier to form into desired shapes. To anneal metal, it must be heated above a critical temperature, maintained at that temperature, and then allowed to cool. For steel, that critical temperature is the transformation temperature to austenite or austenite/cementite. If a metal is annealed for too long it is considered to be "over-aged," and in this state, it has very few dislocations and is very ductile. Heating the metal to a red-hot temperature causes the atoms to move faster and more freely. By slowly cooling from this high temperature, the atoms are able to adopt more ordered arrangements and create a more perfect crystal. The more perfect the crystal of the metal, the easier atoms can "slide" past one another, and thus, the more easily the metal can bend. The material also tends to have large grains after annealing and slow cooling (see Figure 1), and this leads to a more malleable material. In contrast, to make a metal hard and brittle through thermal processing, it must be rapidly quenched from high temperature to room temperature. This quick cooling of the metal from red-hot temperatures freezes the atoms into a disordered phase with many defects. Due to the large number of defects, the atoms cannot move easily, and the metal is considered hard to bend and brittle. Quenching a metal such as steel will also cause it to change phases (or atomic arrangements) and sometimes form a phase called martensite (see Figure 2), which is very hard and brittle. See the introductory PowerPoint presentation on the flash drive in the kit for examples of real-world applications where thermal processing is used to modify materials.

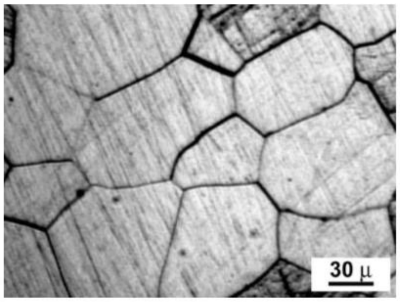

Figure 1. Grain structure of polycrystalline metal

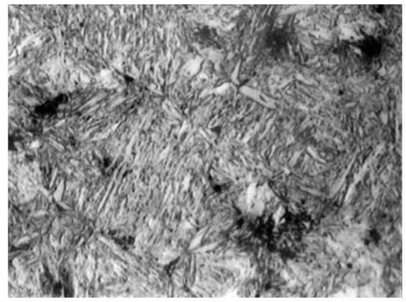

Figure 2. Martensitic grain structure of quenched steel

Lab Description: In this lab, students will see how thermal treatment of a normal steel bobby pin can influence its mechanical properties, especially strength, ductility, and deflection. This will be done using a control sample, an annealed sample, and a quenched sample.

Keywords:

· thermal processing – using temperature changes to impact material properties.
· annealing – heating a material and allowing it to cool slowly.
· quenching – heating a material and forcing it to cool quickly.
· strength – the ability of a material to withstand applied stress without failure.
· stiffness – the ability of a material to withstand deformation (bending).
· elasticity – the ability of a material to deform non-permanently without breaking.
· plasticity – the ability of a material to deform permanently without breaking.
· ductility – the ability of a material to deform under tensile stress.
· malleability – the ability of a material to deform under compressive stress.
· over-aging – having been annealed for too long, which decreases the desired properties of the material.
· deflection – the amount of displacement experienced by a structural element (e.g., beam) under a load.
· elastic modulus – the tendency of a material to deform elastically (i.e., not permanently).
· microstructure – the structure of a material observed through microscopic examination.
· grain – an individual crystal in a polycrystal.
· dislocation – a defect or irregularity in the ordered arrangement of atoms in a material.

Materials List:

Items provided in the kit

· one package of bobby pins
· five plastic cups with twine
· one hole punch
· five C-clamps
· one mass balance

Items to be provided by the teacher/school

· Bunsen burners (one per group)
· pliers or tongs (something for the students to hold the bobby pins with during heating)
· pennies (300 per group)
· ruler
· cup filled with cold water (styrofoam/paper/plastic disposable cups – cheapest you can find works)

Safety Precautions: Proper care and procedures should be used when handling the Bunsen burners, including wearing safety glasses. Remove the plastic tips from bobby pins if present. The bobby pins will get very hot during heating. Do not touch the bobby pins until they have cooled.

Instructions:

1. Set aside one pin to be used as the "control." The control sample will not receive any heat treatment and will be tested "as received."
2. Heat a second pin using the Bunsen burner. The entire pin should be heated until the bobby pin glows red-hot. (***Note:*** *When heating a pin, it is best to use pliers to grip the "open end" of the pin so that it separates the two sides of the pin. This allows the pin to heat much faster.*) Keep the bobby pin in the flame for 20 to 25 seconds after it starts glowing red.
3. After the bobby pin has been removed from the flame and returns to a gray color, set the bobby pin on a paper towel and allow it to continue to cool. This bobby pin has been "annealed."
4. While the second bobby pin is cooling, heat another bobby pin on the Bunsen burner. Place the looped end in the flame, heating the loop and about 1/3 of the pin. The pin should again be kept in the flame until glowing hot for 20 to 25 seconds.
5. Remove the pin from the flame and immediately plunge it into the cup of cold water.
6. Set the bobby pin on a paper towel and allow it to dry completely. This bobby pin has been "quenched."
7. Measure and record the width (mm) and height (mm) of the "smooth" side of the control bobby pin.
8. Punch a hole on each side of the cup and attach the twine as shown in Figure 3. Set up the control bobby pin as shown and be sure that the cup and string are hanging from the end of the bobby pin.

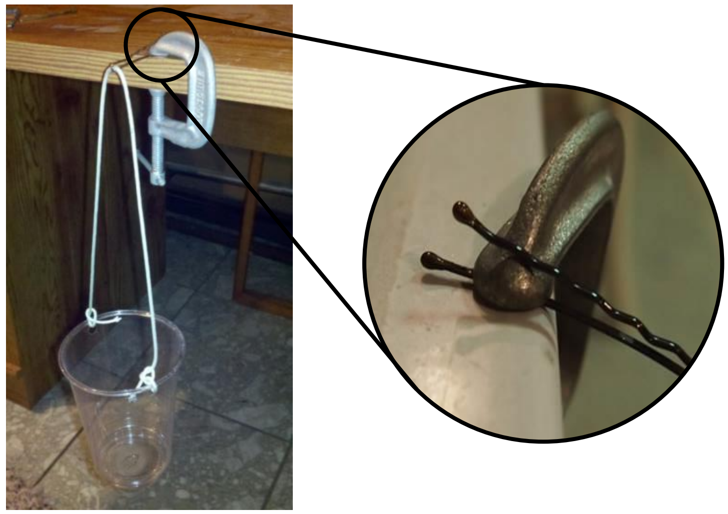

Figure 3. Test set-up

9. Record the length (mm), L, of the control bobby pin that is not supported by the table.
10. Measure and record any deflection that occurred due to the weight of the cup and twine (this will usually be very small, if it is measurable at all). The deflection is how far below the level of the table the far end of the bobby pin has been moved.
11. Create a paper funnel by rolling a piece of paper and either stapling or taping it.
12. Using the funnel, start placing pennies into the cup, one at a time. The pennies should be funneled in at a steady pace, ensuring that each penny lands in the cup before the next penny enters the cup (a pace of two or three pennies per second is good). Try funneling the pennies in a way that they do not fall a large distance when they enter the cup.
13. Add a total of 300 pennies to the cup.
14. Measure and record the deflection of the control bobby pin using a ruler. The typical deflection of a control bobby pin subjected to a load of 300 pennies is 20 to 30mm.
15. Unload the control bobby pin. Measure and record any permanent deflection. The control bobby pin typically has only a slight permanent deflection (usually less than 10mm).
16. Bend the control bobby pin back to its original position to remove the permanent deflection. The control bobby pin should return to its original position.
17. Unclamp the control bobby pin and pull the two sides apart until the control bobby pin forms a straight line. Bend the bobby pin back to its original position. Observe and record any changes that occur during the bending and straightening process. Repeat several more times.
18. Calculate the force applied to the control bobby pin during the penny loading. Find the mass of the cup, string, and the pennies in the cup using the mass balance. The force, P, applied to the bobby pin can then be calculated as follows:

$$P = (\text{mass of cup/twine/pennies})*(\text{gravity} = 9.8\text{m/s}^2)$$

If you do not have access to a mass balance, use the following values to approximate the mass.

a. Mass of one penny = 2.4 grams
b. Mass of the cup and twine = 25 grams

The force, *P*, applied to the bobby pin can then be calculated as follows:

$$P = ((\text{mass of penny})*(\text{\# of pennies}) + \text{mass of cup/twine})*(\text{gravity} = 9.8\text{m/s}^2)$$

19. Calculate the area moment of inertia for the bobby pin:

$$I = \frac{1}{12}bh^3 = \frac{1}{12}*1mm*(0.5mm)^3 = 0.0104mm^4 \text{ (for provided pins)}$$

where *b* is the width of the bobby pin and *h* is the height.

20. Calculate the deflection using the cantilevered beam deflection equation:

$$deflection = \frac{PL^3}{3EI}$$

where *P* = force applied at the end of the bobby pin, *L* = unsupported length of the bobby pin, *E* = modulus of elasticity, and *I* = area moment of inertia. The modulus of elasticity for a steel bobby pin without additional thermal processing is 200,000 N/mm^2.

21. Compare the measured deflection to the calculated deflection.
22. Set up the annealed bobby pin as shown in Figure 3.
23. Add the pennies to the annealed bobby pin in the same fashion as the control bobby pin. Measure and record the deflection of the pin using a ruler. The typical deflection of an annealed bobby pin subjected to a load of 300 pennies is 25 - 30mm (usually slightly higher than the control bobby pin).
24. Unload the pennies from the bobby pin. Measure and record any permanent deflection. The annealed bobby pin typically has a permanent deflection of 20-30mm (much higher than the control bobby pin).
25. Bend the annealed bobby pin back to its original position. The annealed bobby pin may break when you try to do this.
26. If the annealed bobby pin does not break by moving it back to the original position, unclamp the annealed bobby pin and pull the two sides apart until the bobby pin forms a straight line. Bend the bobby pin back to its original shape. Observe and record any changes in the annealed bobby pin during the bending and straightening process. Unlike the control bobby pin, this pin should break after being bent/straightened the first time.
27. Using the cantilevered beam deflection equation given in step 20 and the deflection measured during testing, find the elastic modulus of an annealed bobby pin.

28. Compare the elastic modulus of the annealed bobby pin to the control bobby pin. The elastic moduli of these two pins should be very similar. Annealing does not have an influence on the elasticity of the pin, but on the microstructure.
29. Set up the quenched bobby pin as shown in Figure 3.
30. Load the pennies into the cup being held by the quenched bobby pin in the same fashion as the control bobby pin.
31. If properly quenched, this bobby pin will break before reaching the maximum load of 300 pennies (usually at a loading of ~70 pennies). Carefully monitor the deflection during the loading process. Calculate the deflection using the cantilevered beam equation. The force, *P*, applied to the pin will be based on the number of pennies in the cup at the time of failure of the pin. Assume that the elastic modulus, *E*, of a quenched steel bobby pin is 3000 N/mm^2.
32. Compare the measured deflection at failure to the calculated deflection for a quenched bobby pin.

Demo Delivery Hints: If the calculations become too difficult for younger students, simply compare the deflections (both measured during testing and deflection recovery after testing) and the number of pennies in the cup at failure load. The control, annealed, and quenched pins will behave differently with respect to these properties. For math intensive courses, ask the students to turn in their deflection calculations along with the lab.

Troubleshooting: The pins must remain in the heat long enough to anneal (20 - 25 seconds should be sufficient.) The quenched pin will be very brittle and will likely break after only a light loading (aka small deflection). If the entire pin is heated and then quenched, it will be too brittle to clamp. Therefore, be sure to heat only the 1/3 of the pin towards the looped end (the end that will be loaded) for the quenched bobby pin.

Cleanup/Replacement Parts: Allow the Bunsen burners to completely cool before storing. Dispose of the bent and broken bobby pins. Return the cups with twine, pennies, hole punch, and C-clamps to the kit.

TEACHER DISCUSSION QUESTIONS

Thermal Processing of Bobby Pins

Discussion Questions to Ask Before the Demo

1. What are strength and stiffness?

   Discussion: Strength is the ability of a material to withstand applied stress (or strain) without failure. Stiffness is the ability to withstand deformation (bending).

2. What makes a material strong or stiff?

   Discussion: This actually depends on the microstructure of the material: how the grains are arranged, if there are precipitates or defects in the material, etc.

3. What is plasticity (ductility, malleability)?
   Discussion: Plasticity is a material's ability to plastically deform without breaking. Ductility is specifically in response to tensile stress and malleability to compressive stress.

4. Why are all of these properties important to engineers and architects?

   Discussion: For engineers and architects, all of these properties must be considered when choosing the right material for any structure. Sometimes, a material must be strong enough to withstand the load upon it, for example the weight of cars on a bridge. Other times, a material must be stiff enough not to bend under the applied load. For example, to an engineer designing a new tool or an artist interested in metal jewelry, ductility and malleability are very important (as opposed to just strength), as the material needs these properties to withstand forming processes such as hammering and rolling.

5. How does adding heat affect a material?

   Discussion: The atoms rearrange themselves inside of the material. The heat provides enough energy to allow the motion of the atoms into arrangements of lower energy, which is more energetically favorable.

6. Predict which bobby pin you expect to deflect the most.

   Discussion: Ask this question of students to get them thinking about the differences between the three pins that will be examined. Encourage discussion. There is no right or wrong answer to this question as the students have not yet performed the lab and most likely do not understand the influence of thermal processing on deflection.

Discussion Questions to Ask During the Demo

1. What do you think is happening when the bobby pin is held in the hot flame?

   Discussion: The crystal structure (arrangement of atoms) in the bobby pin is changing, as is the grain structure. The new structure leads to a soft, ductile nature.

2. Will the annealed bobby pin be stronger or weaker than the control bobby pin?

   Discussion: Ask students to make a prediction before testing and explain why they chose this prediction. Encourage them to consider what the processing has done to the bobby pin and how they think that will influence the bobby pin.

3. What is happening when the bobby pin is placed into the cold water after annealing, instead of cooling on the paper towel?

   Discussion: The atoms are being frozen into their hot temperature positions, which is a more disordered crystal.

4. Will the quenched bobby pin be stronger or weaker than the control bobby pin?

   Discussion: Ask students to make a prediction before testing and explain why they chose this prediction. Encourage them to consider what the processing has done to the bobby pin and how they think that will influence the bobby pin.

Discussion Questions to Ask After the Demo

1. Did your prediction of which bobby pin should deflect the most match your experimental results?

   Discussion: The annealed pin should deflect the most. The quenched pin should break under even small loadings. Encourage students to discuss their predictions and why they were either the same or different than the experimental results.

2. Why did the annealed bobby pin deflect with much less load then the control pin?

   Discussion: To anneal the pin, heat is used. This heat provides enough energy for the atoms of the material to rearrange themselves. This allows the grains to grow larger and for dislocations in the material to be destroyed. Less dislocations allow materials to bend more easily.

3. Why is the quenched bobby pin brittle?

   Discussion: The microstructure of the pin has been changed. It is now martensite, a very strained crystal structure with a large number of dislocations and many carbon precipitates. Martensite also has a very needle-like microstructure which results in brittle behavior.

STUDENT LAB HANDOUT

Thermal Processing of Bobby Pins

Introduction: A material can possess a variety of different mechanical properties such as strength, stiffness, plasticity, elasticity, and deflection. Deflection is the amount of displacement experienced by a material when placed under a load. This property is of great importance in building construction, and building codes often specify a maximum allowable deflection, generally as a fraction of the length of the beam. A material's mechanical properties are dependent on the material's microstructure, including the phases present, the number and arrangement of dislocations, and the grain size and shape.

Thermal processing uses heat to change the crystal structure, defect structure (dislocations), and/or grain structure of a material. Heating a metal to red-hot and then allowing it to cool slowly is called annealing. By heating the metal, the atoms are given enough energy to move faster and more freely. Slow cooling allows the atoms to arrange themselves in low energy positions, specifically to create highly ordered crystal structures. When a metal's crystal structure is highly ordered, the atoms can slide past one another more easily, making the metal easy to bend. If a metal is annealed for too long it is considered to be "over-aged," and in this state, it has very few dislocations and is very ductile. To make a metal hard and brittle through thermal processing, it must be rapidly quenched from high temperature to room temperature. This quick cooling of the metal from red-hot temperatures freezes the atoms into a disordered phase with many defects. Due to the large number of defects, the atoms cannot move easily, and the metal is considered hard to bend and brittle.

Lab Description: In this lab, you will see how thermal treatment of a normal steel bobby pin can influence its mechanical properties, especially strength and ductility. This will be done using a control sample, an annealed sample, and a quenched sample.

Keywords: Thermal processing, annealing, strength, stiffness, elasticity, plasticity, ductility, malleability, over-aging, deflection, elastic modulus, microstructure, grain, dislocation

Materials List:
- three bobby pins
- one cup with twine
- one C-clamp
- ruler
- one Bunsen burner

·one pair of pliers or tongs (something to hold the bobby pins during heating)
· ~300 pennies
· one cup filled with cold water

Safety Precautions: Proper care and procedures should be used when handling the Bunsen burners, including wearing safety glasses. The bobby pins will get very hot during heating. Do not touch the bobby pins until they have cooled!

Instructions:

1. Set aside one pin to be used as the "control." The control sample will not receive any heat treatment, and will be tested "as received."
2. Heat a second pin using the Bunsen burner. The entire pin should be heated until the bobby pin glows red-hot. (When heating a pin, it is best to use pliers to grip the "open end" of the pin so that it separates the two sides of the pin. This allows the pin to heat much faster.) Keep the bobby pin in the flame for 20 - 25 seconds after it starts glowing red.
3. After the bobby pin has been removed from the flame and returns to a gray color, set the bobby pin on a paper towel and allow it to continue to cool for several minutes. This bobby pin has been "annealed."
4. While the second bobby pin is cooling, heat another bobby pin using the Bunsen burner. Place the looped end in the flame, heating the loop and about 1/3 of the pin. The pin should again be kept in the flame until glowing hot for 20 - 25 seconds.
5. Remove the pin from the flame and immediately plunge it into the cup of cold water.
6. Set the bobby pin on a paper towel and allow it to dry completely. This bobby pin has been "quenched."
7. Measure and record the width (mm) and height (mm) of the "smooth" side of the control bobby pin.
8. Punch a hole in each side of the cup and attach the twine as shown in Figure 1. Set up the control bobby pin as shown and be sure that the cup and string are hanging from the end of the bobby pin.

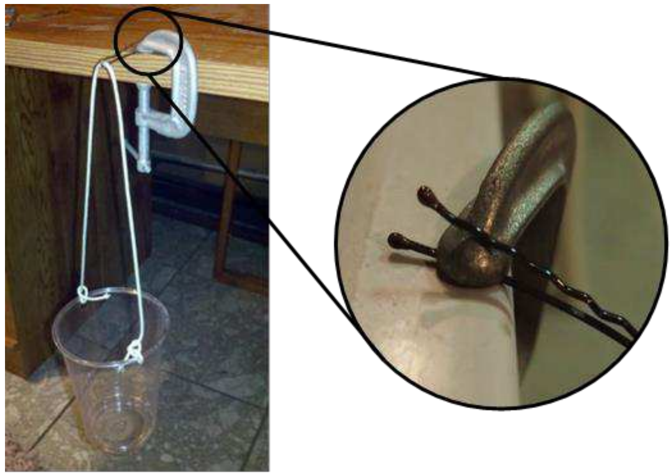

Figure 1 – Test set up

9. Record the length (mm), L, of the control bobby pin that is not supported by the table.
10. Measure and record any deflection that occurred due to the weight of the cup and twine (this will usually be very small, if it is measurable at all). The deflection is how far below the level of the table the far end of the bobby pin has been moved.
11. Create a paper funnel by rolling a piece of paper and either stapling or taping it closed. Using the funnel, start placing pennies into the cup, one at a time. The pennies should be funneled in at a steady pace, ensuring that each penny lands in the cup before the next penny enters the cup (a pace of two to three pennies per second is good). Try funneling the pennies in a way that they do not fall a large distance when they enter the cup.
12. Add a total of 300 pennies to the cup. Measure and record the deflection of the control bobby pin using a ruler.
13. Unload the pennies from the control bobby pin. Measure and record any permanent deflection.
14. Bend the control bobby pin back to its original position to remove the permanent deflection.
15. Unclamp the control bobby pin and pull the two sides apart until the bobby pin forms a straight line. Bend the control bobby pin back to its original position. Observe and record any changes that occur during the bending and straightening process. Repeat several more times.
16. Calculate the force applied to the control bobby pin during the penny loading. Find the mass of the cup, string, and the pennies in the cup using a mass balance. The force, P, applied to the bobby pin can then be calculated as follows:

P = (mass of cup/twine/pennies)*(gravity = 9.8m/s^2)

If you do not have access to a mass balance, use the following weights to approximate the mass.

a. Mass of one penny = 2.4 grams
b. Mass of the cup and twine = 25 grams

The force, P, applied to the bobby pin can then be calculated as follows:

P = ((mass of penny)*(# of pennies) + weight of cup/twine)*(gravity = 9.8m/s^2)

17. Calculate the area moment of inertia, I, for the bobby pin:

$$I = \frac{1}{12}bh^3 = \frac{1}{12} * 1mm * (0.5mm)^3 = 0.0104mm^4 \text{ (for provided pins)}$$

where b is the width of the bobby pin and h is the height.

18. Calculate the deflection using the cantilevered beam deflection equation:

$$deflection = \frac{PL^3}{3EI}$$

where P = force applied at the end of the bobby pin, L = unsupported length of the bobby pin, E = modulus of elasticity, and I = area moment of inertia. The modulus of elasticity for a steel bobby pin is 200,000 N/mm^2.

19. Compare the measured deflection to the calculated deflection.
20. Set up the annealed bobby pin as shown in Figure 1. Load the pennies into the cup being held by the annealed bobby pin in the same fashion as the control bobby pin. Measure and record the deflection of the annealed bobby pin using a ruler.
21. Unload the pennies from the annealed bobby pin. Measure and record any permanent deflection.
22. Bend the annealed bobby pin back to its original position. The bobby pin may break when you try to do this. If the annealed bobby pin does not break by moving it back to the original position, unclamp the bobby pin and pull the two sides apart until the annealed bobby pin forms a straight line. Bend the annealed bobby pin back to its original shape. Observe and record any changes in the bobby pin during the bending and straightening process.
23. Using the cantilevered beam deflection equation given in step 17 and the deflection measured during testing, find the elastic modulus of an annealed bobby pin.

24. Compare the elastic modulus of the annealed bobby pin to the control bobby pin.
25. Set up the quenched bobby pin as shown in Figure 1. Load the pennies into the cup being held by the quenched bobby pin in the same fashion as the control bobby pin.
26. Carefully monitor the deflection during the loading process. Calculate the deflection using the cantilevered beam equation. The force, *P*, applied to the pin will be based on the number of pennies in the cup at the time of failure of the pin. Assume that the elastic modulus, *E*, of a quenched steel bobby pin is 3000 N/mm^2.
27. Compare the measured deflection at failure to the calculated deflection for a quenched bobby pin.

Cleanup/Replacement Parts: Allow the Bunsen burners to completely cool before storing. Dispose of the bent and broken bobby pins. Return the cups with twine, pennies, and C-clamps to your teacher.

STUDENT QUESTION HANDOUT

Thermal Processing of Bobby Pins

Processing History	Total Pennies Added	Maximum Load Applied	Maximum Deflection Measured	Maximum Deflection Calculated
As Received				
Annealed				
Quenched				

1. What makes a material strong or stiff?

2. How is the microstructure of the bobby pin changing when it is heated up?

3. Why would one want to be able to soften a metal?

4. What is happening differently in the quenched bobby pin than the annealed bobby pin? Why does this change the material behavior?

5. Are your measured deflections and calculated deflections similar? If not, what could explain the difference?

6. Compare the deflection and elastic modulus of the control, annealed, and quenched bobby pins.