

Materials Science and Engineering Laboratory

C. H. Hsu
Department of Mechanical Engineering, Mechatronic Engineering,
and Manufacturing Technology

California State University, Chico

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Hardness Tests

Objectives:

1. To learn about principles and different methods of hardness measurement.
2. To learn about the correlations among different types of hardness measurement and correlations of hardness with tensile strength.
3. To acquire experience of using various types of hardness testers.

Background:

Hardness is resistance of a material to plastic indentation, scratching, surface penetration, or wear. These properties are all related to the resistance against plastic flow (permanent deformation) in the material.

There are different approaches and criteria for hardness measurement. Some test methods for certain material provide convenient correlation of hardness to other mechanical properties. For example, hardness from indentation tests on steel and copper alloys can be used as a rough guide to estimate tensile strength. Hardness tests, in most cases, are rapid and repeatable, and in many instances nondestructive. Therefore, hardness test represents an important means of quality control.

All the widely used hardness measurements adopt one of the two general methods: static indentation and rebound testing. Static indentation involves pressing a ball, diamond, or other types of indenter under a specified constant load into the surface of material and measuring the length, width, or depth of the indentation. Each hardness test method, or scale, is defined with a particular type of indenter, a specified minor load, and a specified major load. The measured indentation size is then converted to a hardness number specific to the scale adopted. In general, the harder the material, the better the resistance, and thus the smaller the indentation.

Rebound testing involves dropping an indenter onto the surface of specimen and measuring rebound height of the indenter. The potential energy at the initial height is converted to kinetic energy when the indenter is released. A fraction of the kinetic energy is consumed for plastic deformation on impact, leaving some kinetic energy after impact to convert back to potential energy and achieve a certain rebound height of the indenter. The rebound height measured by the instrument is then converted to a hardness number.

Mohs Testing

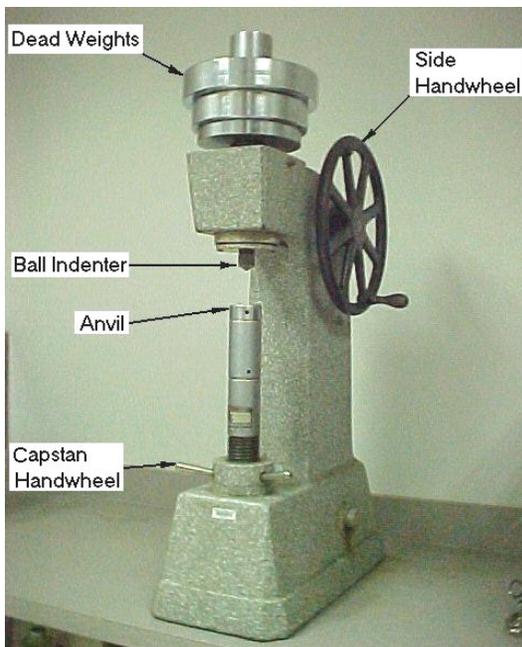
In general, a material will scratch another material of lesser hardness. The Mohs scale is a semi-quantitative scale designed to take advantage of this fact. Ten minerals are numbered from one to ten in order of increasing hardness:

- | | | | | |
|---------------|-----------|------------|-------------|-------------|
| 1. Talc | 2. Gypsum | 3. Calcite | 4. Fluorite | 5. Apatite |
| 6. Orthoclase | 7. Quartz | 8. Topaz | 9. Corundum | 10. Diamond |

However, the hardness of these ten minerals is not regularly spaced. The numbers serve only to designate hardness relative to the hardness of a set of minerals. A substance that scratches quartz but not topaz, for example, has a Mohs hardness between 7 and 8. Since the Mohs testing does not provide sufficient accuracy, it is not commonly used in hardness measurement of typical engineering materials.

Brinell Hardness Testing

Brinell test is performed by pressing a hardened steel ball, 10 mm in diameter, into the flat surface of a sample under a constant load. The load is usually 3000 kg (both dead weights on holder) held for 10 to 15 s for steel and hard metals or 500 kg (only the smaller dead weight on holder) held for about 30 s for soft non-ferrous metals such as copper and aluminum alloys. The specified time period is necessary to ensure that plastic flow during indentation in the metal has stopped. A Brinell hardness tester is shown in Figure 1.



The Brinell hardness number (HB or BH number) is determined by dividing the load by the surface area of the circular indentation seen on the surface according to the formula:

$$HB = \frac{2P}{\pi D \left(D - \sqrt{D^2 - d^2} \right)} \quad (1)$$

where P is the applied load in kg , D is the diameter of the indenter ball in mm , d is the mean diameter in mm of the indentation, and HB is in kg/mm^2 . The mean diameter of the indentation (two readings at right angles to each other) is measured using a microscope.

Figure 1 – A Brinell hardness tester.

The indentation is a result of plastic deformation under the applied load. Unfortunately, different metals respond somewhat differently to a given load exceeding their yield strength. Some metals, for example, work harden more easily during plastic deformation than others. Such metals may give hardness readings lower than that of a material that shows little work hardening when the two are compared under light loads yet give higher hardness readings when compared under heavy loads.

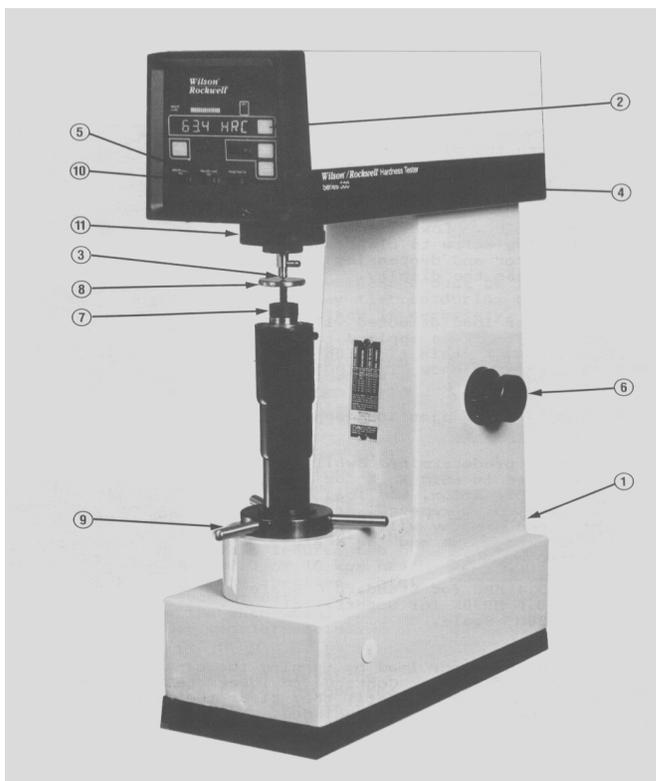
For Brinell hardness test the sample should be flat and securely supported. The sample should be thick enough so that no bulge appears on the opposite (bottom) face during indentation. To ensure accurate results, indentations should not be made too close to the edge of the test piece. Lack of supporting material from one side of the test piece may result in larger and unsymmetrical indentations. Similarly, indentations should not be made too close to one another. Otherwise, the metal may work harden and affect the second indentation or there may not be sufficient supporting material for the second indentation.

Procedure for Brinell hardness test:

1. Place the specimen on the anvil with its surface normal to the direction of applied load.
2. Place the correct weights (two for 3000 kg and only the small one for 500 kg) on the yoke.
3. Turn the large side handwheel in counterclockwise direction until it stops. Hold it in place with right hand.
4. Using left hand, raise the anvil with the capstan handwheel tuning in clockwise direction until the specimen just makes contact with the ball indenter. See that the ball is at least 5 mm from the edges of the specimen or existing indentations.
5. Apply load by slowly turning the side handwheel clockwise until the yoke and weights rise and float for 15 s (under 3000 kg weight) or 30 s (under 500 kg weight).
6. Release the load gradually with the side handwheel slowly turning in the opposition (counter-clockwise) direction. Make sure this is done gently to avoid dynamic load from rapid descend of the weights and the holder.
7. Lower the specimen by turning the capstan handwheel counter-clockwise until it clears the indenter.
8. Measure the diameter of the indentation to the nearest 0.1 mm using a microscope.
9. Calculate the Brinell hardness numbers using Equation (1) with measured parameters in correct units.

Rockwell Hardness Testing

A typical Rockwell hardness tester is shown in Figure 2.



1. Power switch
2. Test scale scroll key
3. Indenter
4. Indenter display
5. Major load (kg) display
6. Weight selector dial
7. Anvil
8. Specimen
9. Capstan handwheel
10. Minor load (kg) display

Figure 2 – A Wilson Rockwell Model 520 hardness tester.

Rockwell hardness test differs from Brinell hardness test in that the hardness is determined from the depth of indentation made by the indenter under a constant load. Various

types of indenters may be used in Rockwell hardness tests: diamond indenter and steel-ball indenters of diameter 1/16, 1/8, 1/4, or 1/2 in. In the test the indenter is pressed into the specimen surface under an initial minor (light) load followed by a major (heavy) load. The additional depth of indentation made by the indenter under the major load beyond that by the minor load is measured and converted to a hardness number (see Table 1). The hardness number is inversely related to the depth of indentation.

There are two basic types of Rockwell hardness tests: regular hardness test and superficial hardness test. Both use hardness tester of similar basic mechanical principles and measure similar criteria with a diamond or a steel ball indenter. In regular Rockwell hardness tests, the minor load is always 10 kg while the major load can be 60, 100, or 150 kg. A letter is assigned to each scale that employs a particular combination of indenter and major load as shown in Figure 5. A hardness number is suffixed by first the letter H (for hardness), then the letter R (for Rockwell), and finally the letter that indicates the scale used. For example, a value of 45 on the Rockwell C scale is expressed as 45 HRC.

In superficial hardness measurement, the minor load is 3 kg and the major load 15, 30, or 45 kg. The superficial hardness scale is designed by a number indicating the major load and a letter N for diamond indenter, T for 1/16-in. ball indenter, W for 1/8-in. ball indenter, X for 1/4-in. ball indenter, or Y for 1/2-in. ball indenter. A superficial hardness number is suffixed by first the letter H (for hardness), then the letter R (for Rockwell), and finally the scale designation. For example, 50 HR30T means a value of 50 is obtained using a 1/16-in. ball indenter with 30 kg major load.

The Rockwell test is more rapid and leaves a smaller and less conspicuous indentation on the workpiece than does the Brinell test. To ensure accuracy, the test surface should be flat and free from scale, pits, and foreign materials. Oiled surfaces generally give slightly lower readings than dry ones because of reduced friction under the indenter. The bottom surface also should be free from scale, dirt, or other foreign substances that might crush or flow under the test pressure and so affect the results.

When the Rockwell hardness tester is used to test the hardness of polymers, a 15-second delay during loading of major load and before the measurement of indenter penetration is allowed to account for the viscoelastic property of polymers. The scale is also specified with a user-selected indenter and a specified major load (60, 100, or 150 kg). For hardness comparison, the same types of indenter and applied load should be used.

Procedure for regular Rockwell hardness test (Wilson/Rockwell tester):

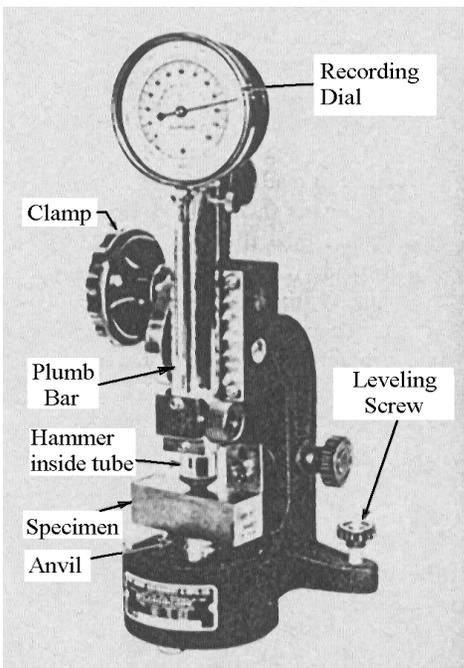
1. Turn power switch located in lower rear panel "ON".
2. Select desired scale by means of the "TEST SCALE SCROLL". This key may be depressed for each scale advancement or held in for rapid scrolling.
3. Select and install the proper indenter, as indicated in the "PENETRATOR" display.
4. Select the proper major load, as indicated in the "MAJOR LOAD kg" display, by means of the weight selector dial.
5. Place the specimen on the anvil.
6. Raise specimen into contact with the indenter by turning capstan handwheel clockwise slowly. The bar LEDs (red) will light up and the read display will show "MINOR LD".

7. Continue to slowly turn the capstan handwheel. Stop the handwheel when the bar LEDs reach the "SET" zone. The major load will automatically be applied and then removed. The read display will show "TESTING" and then the numerical value and the scale tested.
8. Remove the minor load by turning the capstan handwheel counter-clockwise. Continue to lower the specimen until it clears the indenter. The test is concluded.

Procedure for superficial Rockwell hardness test (Kentrell hardness tester):

1. Select proper indenter and anvil.
2. Put gage level pin in "S" position.
3. Screw in upper pins (minor load for superficial hardness test).
4. Select proper major load (lower pins).
5. Select proper gage index.
6. Set depth knob on side of yester (make one test holding indenter bar down until two seconds after dial gage needle comes to rest, set depth knob in accordance with dial gage reading for continuous testing).
7. Place the specimen on the anvil.
8. Raise specimen into contact with the indenter by turning handwheel clockwise slowly until the short gage needle roughly points to the black short downward arrow and the long gage needle points to the start arrow (red or green depending on the selected dial index). Use the adjusting ring to line up the gage index with the needle, if necessary. **DO NOT TURN THE CAPSTAN HANDWHEEL COUNTERCLOCKWISE TO MOVE THE NEEDLE BACKWARD.**
9. Press the indenter bar to applied the major load. The long gage needle points to the measured hardness after a few seconds.
10. Remove the minor load by turning the capstan handwheel counter-clock, and continue until the specimen clears the indenter.

Scleroscope Hardness Testing



The Scleroscope hardness test is essentially a dynamic indentation test. In the test, the height of rebound of a diamond-tipped hammer dropped from a fixed initial height onto the test surface is measured and converted to a hardness value. As the hammer is dropped on a hard material a small fraction of the kinetic energy of the hammer is consumed in plastic deformation of the test surface upon impact. Therefore, with greater amount of remaining energy, the hammer rebounds higher than does on a soft material, giving a higher hardness value. A higher hardness number (Shore number) represents a greater hardness. A Scleroscope hardness tester is shown in Figure 3.

Figure 3 – A Sclerodcope hardness tester.

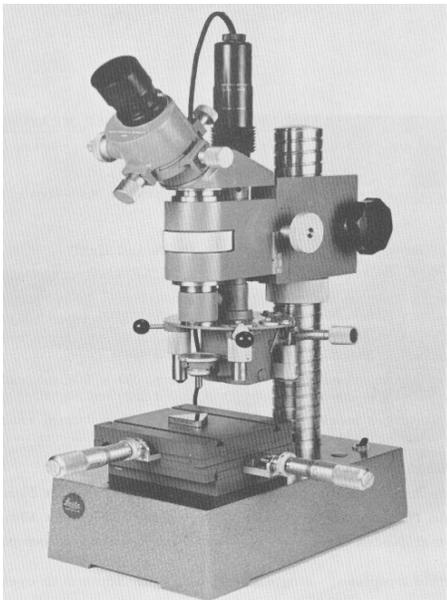
This test method is not reliable on polymers that are inherently bouncy since they tend to bounce the indenter to a height giving a false hardness.

Procedure for Scleroscope hardness test:

1. Place the Scleroscope on a bench and adjust the leveling screws so that the plumb bar hangs freely in the center of the ring at its lower end.
2. Place the specimen on the anvil.
3. Lower the hammer tube onto the specimen surface with the clamp handle. Maintain a slight pressure on the clamp handle during the test.
4. Turn the release knob clockwise (all the way) to release the hammer.
5. Read the Shore hardness number indicated on the dial.
6. Make five measurements on each specimen. Do not let the hammer fall on the same spot twice to avoid work hardening.

Microhardness Testing

The term microhardness is generally referring to the size of indentation. In the test, a minute indenter and small constant loads (no more than 1000 g) are usually employed.



Dimensions of the indentation and the load are both used in the determination of the hardness number. There are two similar indenters for microhardness testing: Vickers and Knoop microhardness indenters (Figure 5). Both hardness tests follow the Brinell principle, in that the indenter is pressed under a constant load into the material, the load removed, the size of the indentation measured, and the hardness number calculated by dividing the load by the surface area of indentation. They differ, however, in the shape of the indenter and indentation as shown in Figure 5. The Vickers indenter generates a square impression while Knoop indenter creates an elongated impression.

Figure 4 – A Leitz microhardness tester.

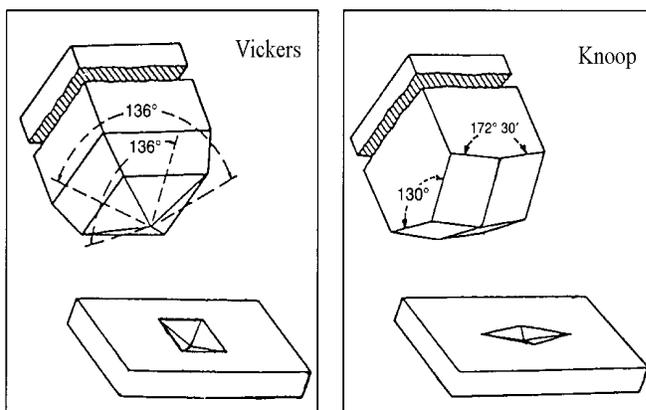


Figure 5 – Diamond indenters for Vickers and Knoop microhardness testers. The Vickers indenter has two identical 136° angles to form a pyramidal indentation; the Knoop indenter has two unique angles to form an elongated indentation.

Vickers Microhardness Testing

A Vickers indenter is used in the Vickers microhardness test. The Vickers microhardness indenter is made of diamond in the form of a square-base pyramid having an angle of 136° between faces as shown in Figure 4. The indenter should be applied under a predetermined constant load for 10 to 15 s. The diagonals of the square indentation are measured using the microscope and a mean value is calculated. The Vickers hardness number (VHN) is then calculated according to the formula:

$$\text{VHN} = 2P \sin(\theta/2) / d^2 = 1854.4P / d^2 \quad (2)$$

where P is the applied load in grams (g), θ is the indenter face angle of 136° , and d is the mean diagonal length in μm . The constant 1854.4 incorporates the value of $\sin(\theta/2)$ and other conversion factors to give VHN a unit of kg/mm^2 .

Knoop Microhardness Testing

The Knoop microhardness indenter is made of diamond in the form of pyramid that has an included longitudinal angle of $172^\circ 30'$ and an included transverse angle of 130° . The indenter generates a diamond-shape indentation having an approximate ratio of 7 to 1 between long and short diagonals. The Knoop hardness number (KHN) is calculated using the formula:

$$\text{KHN} = P/A = 14229P/d^2 \quad (3)$$

where P is the applied load in grams (g), A is the indentation area, d is the measured length of long diagonal of the indentation in μm , and 14229 is the constant relating projected area of the indentation to the square of the length of the long diagonal.

Procedure for microhardness test:

1. Turn on the tester.
2. Select and install the indenter (Vickers or Knoop), if not already installed.
3. Place the weights selected on the loading pan.
4. Place the specimen in the tester and turn the $40\times$ objective lens into place. Focus on the specimen surface with the focusing control until surface features can be seen.
5. Gently turn the loading handle clockwise to raise the weights and the indenter, and turn the indenter into place. Slowly release the loading handle counter-clockwise to apply the load. Leave the indenter on the specimen for 10 to 15 s.
6. Raise the indenter by turning the loading handle clockwise gently, and turn the objective lens back into place.
7. Focus on the specimen surface to view the indentation. Measure length of the long diagonal (Knoop) or both diagonals (Vickers) of the indentation with the scale in the microscope. The numbers on the scale are length measured in 0.001 mm. Alternatively, the diagonal lengths can be determined by moving a point on the scale from a corner to the opposite corner of the impression under microscope and noting the difference in micrometer readings (numbers on the fine scale are in 0.01 mm).
8. Calculate microhardness number using the appropriate formula.

Hardness-Tensile Strength Correlations:

It is difficult to develop precise correlations between hardness from different measuring methods, or with other mechanical properties. Approximate relations, however, can be found for the same material using different hardness tests. Tables 2 and 3 are useful for approximate conversion of hardness from various hardness testing methods.

There is also no direct correlation between indentation hardness and yield strength from a tension test since far more plastic deformation is involved in the hardness tests than that involved before yielding of material in tension test. However, because the plastic deformation involved in the tests for ultimate tensile strength is similar to that in hardness tests, empirical relations exist between these two properties. Based on Brinell hardness, for steels:

$$\text{Ultimate Tensile Strength (MPa)} \approx 3.5 \times (\text{Brinell Hardness}) \quad (4)$$

and for brass:

$$\text{Ultimate Tensile Strength (MPa)} \approx 80 + 2.9 \times (\text{Brinell Hardness}) \quad (5)$$

Table 1 – Various hardness testing methods.

Test	Indenter	Shape of Indentation		Load	Formula for Hardness Number	
		Side View	Top View			
Macro-hardness tests						
Brinell	10-mm sphere of steel or tungsten carbide			P (kg)	$BH = \frac{2P}{\pi D(D - \sqrt{D^2 - d^2})} \text{ (kg/mm}^2\text{)}$	
Micro-hardness tests						
Rockwell	Diamond tip cone			60 (kg)	$R_A =$	
				150 (kg)	$R_C =$	
				100 (kg)	$R_D =$	
	B } F } G }	$\frac{1}{16}$ -in. diameter steel sphere			100 (kg)	$R_B =$
					60 (kg)	$R_F =$
				150 (kg)	$R_G =$	
	$\frac{1}{8}$ -in. diameter steel sphere			100 (kg)	$R_E =$	
Vickers	Diamond pyramid			P (g)	$VHN = 1854.4P/d^2 \text{ (kg/mm}^2\text{)}$ **	
Knoop	Diamond pyramid			P (g)	$KHN = 14229P/d^2 \text{ (kg/mm}^2\text{)}$ ***	
		$l/b = 7.11$ $b/t = 4.00$				

* t is the penetration (in mm) of indenter between the applied minor and major loads.

** See Equation (2) for correct units for applied load and measured lengths.

*** See Equation (3) for appropriate units for applied load and measured lengths.

Table 2 - Hardness Conversion for Hardened Steel and Hard Alloys

C 150 kg Brale	A 60 kg Brale	D 100 kg Brale	15-N 15 kg N Brale	30-N 30 kg N Brale	45-N 45 kg N Brale	HV Vickers 10 kg	HK 500 gm & over	HB 3000 kg 10-mm Ball	G 150 kg 1/16" Ball	ksi 1000 psi
Rockwell	Rockwell	Rockwell	Superficial	Superficial	Superficial	Vickers	Knoop	Brinell	Rockwell	Tensile Strength
80	92.0	86.5	96.5	92.0	87.0	1865	---	↑	↑	↑
79	91.5	85.5	96.3	91.5	86.5	1787	---			
78	91.0	84.5	96.0	91.0	85.5	1710	---			
77	90.5	84.0	95.8	90.5	84.5	1633	---			
76	90.0	83.0	95.5	90.0	83.5	1556	---			
75	89.5	82.5	95.3	89.0	82.5	1478	---			
74	89.0	81.5	95.0	88.5	81.5	1400	---			
73	88.5	81.0	94.8	88.0	80.5	1323	---	Note 1		Note 2
72	88.0	80.0	94.5	87.0	79.5	1245	---			
71	87.0	79.5	94.3	86.5	78.5	1160	---			
70	86.5	78.5	94.0	86.0	77.5	1076	972			
69	86.0	78.0	93.5	85.0	76.5	1004	946			
68	85.6	76.9	93.2	84.4	75.4	940	920			
67	85.0	76.1	92.9	83.6	74.2	900	895			
66	84.5	75.4	92.5	82.8	73.3	865	870	N/A		
65	83.9	74.5	92.2	81.9	72.0	832	846	739		
64	83.4	73.8	91.8	81.1	71.0	800	822	722		
63	82.8	73.0	91.4	80.1	69.9	772	799	706		
62	82.3	72.2	91.1	79.3	68.8	746	776	688		
61	81.8	71.5	90.7	78.4	67.7	720	754	670		
60	81.2	70.7	90.2	77.5	66.6	697	732	654		N/A
59	80.7	69.9	89.8	76.6	65.5	674	710	634		351
58	80.1	69.2	89.3	75.7	64.3	653	690	615		338
57	79.6	68.5	88.9	74.8	63.2	633	670	595		325
56	79.0	67.7	88.3	73.9	62.0	613	650	577		313
55	78.5	66.9	87.9	73.0	60.9	595	630	560		301
54	78.0	66.1	87.4	72.0	59.8	577	612	543		292
53	77.4	65.4	86.9	71.2	58.8	560	594	525		283
52	76.8	64.6	86.4	70.2	57.4	544	576	512		273
51	76.3	63.8	85.9	69.4	56.1	528	558	496		264
50	75.9	63.1	85.5	68.5	55.0	513	542	481		255
49	75.2	62.1	85.0	67.6	53.8	498	526	469		246
48	74.7	61.4	84.5	66.7	52.5	484	510	455	N/A	238

C	A	D	15-N	30-N	45-N	HV	HK	HB	G	ksi	
150 kg Brale	60 kg Brale	100 kg Brale	15 kg N Brale	30 kg N Brale	45 kg N Brale	Vickers 10 kg	500 gm & over	3000 kg 10-mm Ball	150 kg 1/16" Ball	1000 psi	
Rockwell	Rockwell	Rockwell	Superficial	Superficial	Superficial	Vickers	Knoop	Brinell	Rockwell	Tensile Strength	
47	74.1	60.8	83.9	65.8	51.4	471	495	443	↑	229	
46	73.6	60.0	83.5	64.8	50.3	458	480	432		221	
45	73.1	59.2	83.0	64.0	49.0	446	466	421		215	
44	72.5	58.5	82.5	63.1	47.8	434	452	409		208	
43	72.0	57.7	82.0	62.2	46.7	423	438	400		201	
42	71.5	56.9	81.5	61.3	45.5	412	426	390		194	
41	70.9	56.2	80.9	60.4	44.3	402	414	381		188	
40	70.4	55.4	80.4	59.5	43.1	392	402	371		182	
39	69.9	54.6	79.9	58.6	41.9	382	391	362		177	
38	69.4	53.8	79.4	57.7	40.8	372	380	353		171	
37	68.9	53.1	78.8	56.8	39.6	363	370	344		166	
36	68.4	52.3	78.3	55.9	38.4	354	360	336		161	
35	67.9	51.5	77.7	55.0	37.2	345	351	327		156	
34	67.4	50.8	77.2	54.2	36.1	336	342	319		152	
33	66.8	50.0	76.6	53.3	34.9	327	334	311		149	
32	66.3	49.2	76.1	52.1	33.7	318	326	301		146	
31	65.8	48.4	75.6	51.3	32.5	310	318	294		N/A	141
30	65.3	47.7	75.0	50.4	31.3	302	311	286		92.0	138
29	64.6	47.0	74.5	49.5	30.1	294	304	279	91.0	135	
28	64.3	46.1	73.9	48.6	28.9	286	297	271	90.0	131	
27	63.8	45.2	73.3	47.7	27.8	279	290	264	89.0	128	
26	63.3	44.6	72.8	46.8	26.7	272	284	258	88.0	125	
25	62.8	43.8	72.2	45.9	25.5	266	278	253	87.0	123	
24	62.4	43.1	71.6	45.0	24.3	260	272	247	86.0	119	
23	62.0	42.1	71.0	44.0	23.1	254	266	243	84.5	117	
22	61.5	41.6	70.5	43.2	22.0	248	261	237	83.5	115	
21	61.0	40.9	69.9	42.3	20.7	243	256	231	82.5	112	
20	60.5	40.1	69.4	41.5	19.6	238	251	226	81.0	110	

Note 1: A 10-mm steel ball is used for 450 HB and below. A carbide ball is used above 450HB.

Note 2: The tensile strength relation to hardness is inexact, even for steel, unless it is determined for a specific material.

**Table 3 – Hardness Conversion for
Soft Steel, Grey and Malleable Cast Iron and Most Non-ferrous Alloys**

B	F	G	15-T	30-T	45-T	E	H	K	A	HK	HB	HB/ HV	ksi
100 kg 1/16" Ball	60 kg 1/16" Ball	150 kg 1/16" Ball	15 kg 1/16" Ball	30 kg 1/16" Ball	45 kg 1/16" Ball	100 kg 1/8" Ball	60 kg 1/8" Ball	150 kg 1/8" Ball	60 kg Brate	500 gm & over	500 kg 10 mm Ball	3000 kg/ 10 kg	1000 psi
Rockwell	Rockwell	Rockwell	Superficial	Superficial	Superficial	Rockwell	Rockwell	Rockwell	Rockwell	Knoop	Brinell	Brinell 10 mm Vickers 136°	Tensile Strength
100	↑	82.5	93.1	83.1	72.9	↑	↑	↑	61.5	251	201	240	116
99		81.0	92.8	82.5	71.9				60.9	246	195	234	114
98		79.0	92.5	81.8	70.9				60.2	241	189	228	109
97		77.5	92.1	81.1	69.9				59.5	236	184	222	104
96		76.0	91.8	80.4	68.9				58.9	231	179	216	102
95		74.0	91.5	79.8	67.9				58.3	226	175	210	100
94		72.5	91.2	79.1	66.9				57.6	221	171	205	98
93		71.0	90.8	78.4	65.9				57.0	216	167	200	94
92		69.0	90.5	77.8	64.8			100	56.4	211	163	195	92
91		67.5	90.2	77.1	63.8			99.5	55.8	206	160	190	90
90		66.0	89.9	76.4	62.8			98.5	55.2	201	157	185	89
89		64.0	89.5	75.8	61.8			98.0	54.6	196	154	180	88
88		62.5	89.2	75.1	60.8			97.0	54.0	192	151	176	86
87		61.0	88.9	74.4	59.8			96.5	53.4	188	148	172	84
86		59.0	88.6	73.8	58.8			95.5	52.8	184	145	169	83
85		57.5	88.2	73.1	57.8			94.5	52.3	180	142	165	82
84		56.0	87.9	72.4	56.8			94.0	51.7	176	140	162	81
83		54.0	87.6	71.8	55.8			93.0	51.1	173	137	159	80
82		52.5	87.3	71.1	54.8			92.0	50.6	170	135	156	77
81		51.0	86.9	70.4	53.8			91.0	50.0	167	133	153	73
80		49.0	86.6	69.7	52.8			90.5	49.5	164	130	150	72
79		47.5	86.3	69.1	51.8			89.5	48.9	161	128	147	70
78		46.0	86.0	68.4	50.8			88.5	48.4	158	126	144	69
77		44.0	85.6	67.7	49.8			88.0	47.9	155	124	141	68
76	N/A	42.5	85.3	67.1	48.8			87.0	47.3	152	122	139	67
75	99.6	41.0	85.0	66.4	47.8			86.0	46.8	150	120	137	66
74	99.1	39.0	84.7	65.7	46.8			85.0	46.3	147	118	135	65
73	98.5	37.5	84.3	65.1	45.8			84.5	45.8	145	116	132	64
72	98.0	36.0	84.0	64.4	44.8	N/A		83.5	45.3	143	114	130	63
71	97.4	34.5	83.7	63.7	43.8	100		82.5	44.8	141	112	127	62
70	96.8	32.5	83.4	63.1	42.8	99.5		81.5	44.3	139	110	125	61
69	96.2	31.0	83.0	62.4	41.8	99.0		81.0	43.8	137	109	123	60
68	95.6	29.5	82.7	61.7	40.8	98.0		80.0	43.3	135	107	121	59

B	F	G	15-T	30-T	45-T	E	H	K	A	HK	HB	HB/HV	ksi
100 kg 1/16" Ball	60 kg 1/16" Ball	150 kg 1/16" Ball	15 kg 1/16" Ball	30 kg 1/16" Ball	45 kg 1/16" Ball	100 kg 1/8" Ball	60 kg 1/8" Ball	150 kg 1/8" Ball	60 kg Brate	500 gm & over	500 kg 10 mm	3000 kg/ 10 kg	1000 psi
Rockwell	Rockwell	Rockwell	Superficial	Superficial	Superficial	Rockwell	Rockwell	Rockwell	Rockwell	Knoop	Brinell	Brinell 10 mm Vickers 136°	Tensile Strength
67	95.1	28.0	82.4	61.0	39.8	97.5		79.0	42.8	133	106	119	58
66	94.5	26.5	82.1	60.4	38.7	97.0		78.0	42.3	131	104	117	57
65	93.9	25.0	81.8	59.7	37.7	96.0		77.5	41.8	129	102	116	56
64	93.4	23.5	81.4	59.0	36.7	95.5		76.5	41.4	127	101	114	N/A
63	92.8	22.0	81.1	58.4	35.7	95.0		75.5	40.9	125	99	112	
62	92.2	20.5	80.8	57.7	34.7	94.5		74.5	40.4	124	98	110	
61	91.7	19.0	80.5	57.0	33.7	93.5		74.0	40.0	122	96	108	
60	91.1	17.5	80.1	56.4	32.7	93.0		73.0	39.5	120	95	107	
59	90.5	16.0	79.8	55.7	31.7	92.5		72.0	39.0	118	94	106	
58	90.0	14.5	79.5	55.0	30.7	92.0		71.0	38.6	117	92	104	Note 2
57	89.4	13.0	79.2	54.4	29.7	91.0		70.5	38.1	115	91	103	
56	88.8	11.5	78.8	53.7	28.7	90.5		69.5	37.7	114	90	101	
55	88.2	10.0	78.5	53.0	27.7	90.0		68.5	37.2	112	89	100	
54	87.7	8.5	78.2	52.4	26.7	89.5		68.0	36.8	111	87	N/A	
53	87.1	7.0	77.9	51.7	25.7	89.0		67.0	36.3	110	86		
52	86.5	5.5	77.5	51.0	24.7	88.0		66.0	35.9	109	85		
51	86.0	4.0	77.2	50.3	23.7	87.5		65.0	35.5	108	84		
50	85.4	2.5	76.9	49.7	22.7	87.0		64.5	35.0	107	83		
49	84.8	N/A	76.6	49.0	21.7	86.5		63.5	34.6	106	82		
48	84.3		76.2	48.3	20.7	85.5		62.5	34.1	105	81		
47	83.7		75.9	47.7	19.7	85.0		61.5	33.7	104	80		
46	83.1		75.6	47.0	18.7	84.5		61.0	33.3	103	80		
45	82.6		75.3	46.3	17.7	84.0		60.0	32.9	102	79		
44	82.0		74.9	45.7	16.7	83.5		59.0	32.4	101	78		
43	81.4		74.6	45.0	15.7	82.5		58.0	32.0	100	77		
42	80.8		74.3	44.3	14.7	82.0		57.5	31.6	99	76		
41	80.3		74.0	43.7	13.6	81.5		56.5	31.2	98	75		
40	79.7		73.6	43.0	12.6	81.0		55.5	30.7	97	75		
39	79.1		73.3	42.3	11.6	80.0		54.5	30.3	96	74		
38	78.6		73.0	41.6	10.6	79.5		54.0	29.9	95	73		
37	78.0		72.7	41.0	9.6	79.0	N/A	53.0	29.5	94	72		
36	77.4		72.3	40.3	8.6	78.5	100	52.0	29.1	93	72		
35	76.9		72.0	39.6	7.6	78.0	99.5	51.5	28.7	92	71		
34	76.3		71.7	39.0	6.6	77.0	99.0	50.5	28.2	91	70		
33	75.7		71.4	38.3	5.6	76.5	98.8	49.5	27.8	90	69		
32	75.2		71.0	37.6	4.6	76.0	98.5	48.5	27.4	89	69		

B	F	G	15-T	30-T	45-T	E	H	K	A	HK	HB	HB/ HV	ksi
100 kg 1/16" Ball	60 kg 1/16" Ball	150 kg 1/16" Ball	15 kg 1/16" Ball	30 kg 1/16" Ball	45 kg 1/16" Ball	100 kg 1/8" Ball	60 kg 1/8" Ball	150 kg 1/8" Ball	60 kg Brake	500 gm & over	500 kg 10 mm Ball	3000 kg/ 10 kg	1000 psi
Rockwell	Rockwell	Rockwell	Superficial	Superficial	Superficial	Rockwell	Rockwell	Rockwell	Rockwell	Knoop	Brinell	Brinell 10 mm Vickers 136°	Tensile Strength
31	74.6		70.7	37.0	3.6	75.5	98.0	48.0	27.0	88	68		
30	74.0		70.4	36.3	2.6	75.0	97.8	47.0	26.6	87	67		
29	73.5		70.0	35.6	1.0	74.0	97.5	46.0	26.0	87	66		
28	73.0		69.3	34.5	N/A	73.5	97.0	45.0	25.5	86	66		
27	72.5		69.5	34.0		73.0	96.5	44.5	25.0	85	65		
26	72.0		69.0	33.0		72.5	96.3	43.5	24.5	84	65		
25	71.0		68.8	32.5		72.0	96.0	42.5	24.3	83	64		
24	70.5		68.5	32.0		71.0	95.5	41.5	24.0	82	64		
23	70.0		68.0	31.0		70.5	95.3	41.0	23.5	82	63		
22	69.5		67.8	30.5		70.0	95.0	40.0	23.0	81	62		
21	69.0		67.5	29.5		69.5	94.5	39.0	22.5	81	62		
20	68.5		67.3	29.0		68.5	94.3	38.0	22.0	80	61		
19	68.0		67.0	28.5		68.0	94.0	37.5	21.5	79	61		
18	67.0		66.5	27.5		67.5	93.5	36.5	21.3	78	60		
17	66.5		66.3	27.0		67.0	93.0	35.5	21.0	78	60		
16	66.0		66.0	26.0		66.5	92.8	35.0	20.5	77	59		
15	65.5		65.5	25.5		65.5	92.5	34.0	20.0	76	59		
14	65.0		65.3	25.0		65.0	92.0	33.0	N/A	75	59		
13	64.5		65.0	24.0		64.5	91.8	32.0		75	58		
12	64.0		64.5	23.5		64.0	91.5	31.5		74	58		
11	63.5		64.3	23.0		63.5	91.0	30.5		73	57		
10	63.0		64.0	22.0		62.5	90.5	29.5		72	57		
9	62.0		63.8	21.5		62.0	90.3	29.0		71	57		
8	61.5		63.5	20.5		61.5	90.0	28.0		71	56		
7	61.0		63.0	20.0		61.0	89.5	27.0		70	56		
6	60.5		62.8	19.5		60.5	89.3	26.0		69	55		
5	60.0		62.5	18.5		60.0	89.0	25.5		69	55		
4	59.5		62.0	18.0		59.0	88.5	24.5		69	55		
3	59.0		61.8	17.0		58.5	88.0	23.5		68	54		
2	58.0		61.5	16.5		58.0	87.8	23.0		68	54		
1	57.5		61.0	16.0		57.5	87.5	22.0		67	54		
0	57.0	▼	60.5	15.0	▼	57.0	87.0	21.0	▼	67	53	▼	▼

Assignments:

1. Observe carefully the demonstration of the operation procedure of the various types of hardness testing machines. Take notes if necessary.
2. Obtain samples for each type of hardness testing from the instructor.
3. Measure the hardness of the samples and record results on the data sheet. Pay attention to units of measured parameters, if any.
4. Submit a report including the datasheet and calculation of hardness numbers and conversions.
5. Answer the following questions in the report:
 - a. Compare the calculated Brinell hardness numbers for the same specimen under two different applied loads (500 kg and 3000 kg). Are the hardness numbers fairly close (within 20%)? If not, can you think of any reason for this obvious discrepancy?
 - b. In Rockwell hardness testing of the brass specimen, estimate the penetration depth of indenter under the major load. Show your calculation.
 - c. Did you notice any functional differences between the Rockwell hardness measurement of metals and that of polymers? Describe the differences, if any, and try to explain the purpose of the differences.
 - d. Examine the Scleroscope hardness test results for various types of material. Do you find anything unusual about the relative hardness of different types of material? Describe what you think is unusual, if any, and try to explain why it happens.

MECH 210 – Materials Science and Engineering Laboratory
Hardness Test Data Sheet

Date: _____

Name: _____

I. Brinell Hardness Test

Material: _____

Thickness: _____

Applied Load:
Diameter of Impression (3 minimum):
Average Diameter:
Standard Deviation:
Brinell Hardness Based on Average Diameter:

Brinell hardness calculation:

Material: _____

Thickness: _____

Applied Load:
Diameter of Impression (3 minimum):
Average Diameter:
Standard Deviation:
Brinell Hardness Based on Average Diameter:

Brinell hardness calculation:

II. Regular Rockwell Hardness Test

Material: _____ Thickness: _____

Scale:	Type of Indenter:
Minor Load:	Major Load:
Measured Hardness (3 minimum):	
Average Hardness:	
Standard Deviation:	
Equivalent Brinell Hardness From Average Rockwell Hardness:	
Estimated Tensile Strength:	

Tensile strength calculation:

Material: _____ Thickness: _____

Scale:	Type of Indenter:
Minor Load:	Major Load:
Measured Hardness (3 minimum):	
Average Hardness:	
Standard Deviation:	
Equivalent Brinell Hardness From Average Rockwell Hardness:	
Estimated Tensile Strength:	

Tensile strength calculation:

Material: _____ Thickness: _____

Scale:	Type of Indenter:
Minor Load:	Major Load:
Measured Hardness (3 minimum):	
Average Hardness:	
Standard Deviation:	
Equivalent Brinell Hardness From Average Rockwell Hardness:	
Estimated Tensile Strength:	

Tensile strength calculation:

III. Superficial Rockwell Hardness Test:

Material: _____ Thickness: _____

Scale:	Type of Indenter:
Minor Load:	Major Load:
Measured Hardness (3 minimum):	
Average Hardness:	
Standard Deviation:	
Equivalent Brinell Hardness From Average Rockwell Hardness:	
Estimated Tensile Strength:	

Material: _____ Thickness: _____

Scale:	Type of Indenter:
Minor Load:	Major Load:
Measured Hardness (3 minimum):	
Average Hardness:	
Standard Deviation:	
Equivalent Brinell Hardness From Average Rockwell Hardness:	
Estimated Tensile Strength:	

IV. Scleroscope Hardness Test

Material: _____ Thickness: _____

Measured Shore Hardness (3 minimum):
Average Shore Hardness:
Standard Deviation:
Equivalent Brinell Hardness From Average Shore Hardness:

Material: _____ Thickness: _____

Measured Shore Hardness (3 minimum):
Average Shore Hardness:
Standard Deviation:
Equivalent Brinell Hardness From Average Shore Hardness:

Material: _____ Thickness: _____

Measured Shore Hardness (3 minimum):
Average Shore Hardness:
Standard Deviation:
Equivalent Brinell Hardness From Average Shore Hardness:

V. Microhardness Test

Material: _____

Thickness: _____

Type:	Type of Indenter:
Applied Load:	
Diagonal Length (major)* (2 minimum):	
Diagonal Length (minor)* (2 minimum):	
Average Diagonal Length:	
Hardness Based on Average Diagonal Length:	

* Measure both diagonal lengths for Vickers hardness, only major (long) diagonal length for Knoop hardness.

Calculation of hardness from average diagonal length:

Tensile Tests

Objectives:

1. Familiarization with a computer-controlled universal testing machine (UTM), standard tensile test and test procedure.
2. Observation of the tensile behavior of metal and polymer materials.
3. Determination of material properties from stress-strain curves obtained from tensile tests.

Background:

Whether a metal is used in an automobile, a bridge, a building or a space vehicle, an important requirement is its ability to withstand and transmit stress. This ability is usually evaluated by tensile tests on standard specimens cut from the particular material. Tensile tests determine the strength characteristics as well as plasticity characteristics.

The term "tensile test" refers to the test in which a prepared specimen is subjected to a gradually increasing uniaxial load until final fracture occurs. Tensile tests are carried out on standard specimens of circular or rectangular cross section. The ends of the specimen are gripped and increasing tensile load is applied to cause the specimen to elongate. The applied load and the change of a gage length on specimen are recorded simultaneously, and used to develop a characteristic stress-strain curve. Useful mechanical properties can then be determined from the stress-strain curve. A schematic stress-strain diagram with property determination for metals is shown in Figure 1.

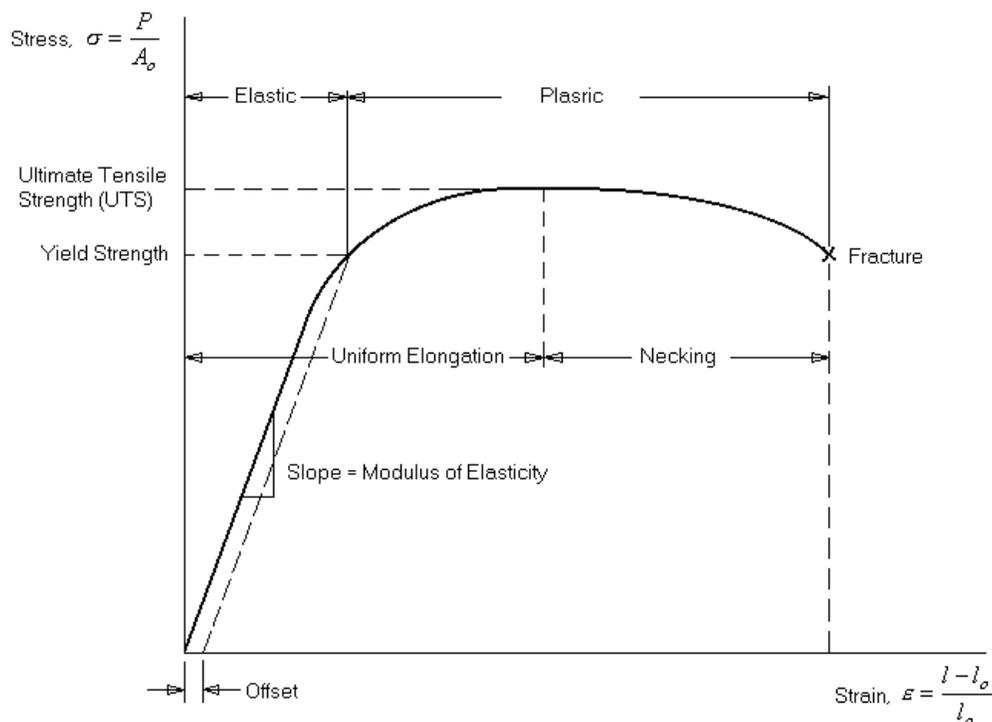


Figure 1 – A schematic stress-strain curve for metals. Typically, an offset of 0.002 (or 0.2%) is used to determine the 0.2% offset yield strength.

The elongation of the specimen initially is proportional to the increasing load, as described by Hooke's law, resulting in a straight stress-strain line segment. Then, at a certain load, the proportionality between the specimen elongation and the applied load is interrupted, causing the stress-strain curve to deviate from the previous straight line. The stress corresponding to the point on the curve where the proportionality ends is termed *proportionality limit*. In the stress range up to the proportionality limit the material behaves elastically where the elongation can be fully recovered upon release of the load. The slope of the straight stress-strain line can be taken as the *modulus of elasticity* E , ratio of stress to strain from Hooke's law:

$$\sigma = E\varepsilon \quad \text{or} \quad E = \sigma/\varepsilon \quad (1)$$

where σ is stress and ε is strain.

With the applied load close to or greater than the proportionality limit, plastic deformation is formed in the material; the specimen does not restore to its original dimensions after the applied load is removed. The transition from the region of elastic deformation to that of plastic deformation occurs gradually; the stress-strain curve deviates from the straight stress-strain line gradually. It is practically impossible to determine a definite location on the stress-strain curve that marks the transition. Instead, a yield point is determined using a specified residual strain (typically 0.2%) and modulus of elasticity as shown in Figure 1. The stress corresponding to the yield point is termed (0.2% offset) *yield strength* of the material. Note that there will be permanent strain (0.2%) when the load is increased to the yield point and fully removed.

Increasing the load above the yield point causes uniform plastic deformation throughout the specimen (within gage length) and results in work hardening of the material. As the material hardens, the load required to elongate the specimen increases until it reaches a maximum level as shown in Figure 1. The stress corresponding to the peak on the stress-strain curve is termed *Ultimate tensile strength*. The ultimate tensile strength marks the point of transition from uniform plastic deformation to localized plastic deformation in a small (usually the weakest) region along the length of the specimen. The local yielding results in a more appreciable local contraction of the cross section with the formation of a "neck". Therefore, the tensile strength characterizes the resistance of a metal to plastic deformation. The reduced cross sectional area results in increased local stress which develops still more local yielding, and therefore decreasing load needed to break the specimen.

Tensile test is among the simplest of all the mechanical tests. Useful properties directly observed and those that can be estimated from tensile tests include: modulus of elasticity, yield strength, tensile strength, ductility in % elongation or % reduction in area, modulus of resilience, and strain hardening exponent.

$$\text{Tensile Strength} = (\text{Maximum Load})/(\text{Original Cross Sectional Area}) \quad (2)$$

$$\text{Yield Strength } (\sigma_y) = \text{Stress at which a material exhibits a specified deviation from proportionality of stress and strain. An offset of 0.2\% is often used.} \quad (3)$$

Modulus of Elasticity (E) = slope (ratio of stress to strain) of linear stress-strain curve in the elastic region. (4)

$$\begin{aligned} \text{Percent Elongation} &= [(\text{Change in gage Length})/(\text{Original Gage Length})]\times 100 \\ &= \left(\frac{l_f - l_o}{l_o} \right) \times 100 \end{aligned} \quad (5)$$

$$\begin{aligned} \text{Percent Reduction in Area} &= [(\text{Change in Cross Sectional Area})/(\text{Original Area})]\times 100 \\ &= \left(\frac{A_o - A_f}{A_o} \right) \times 100 \end{aligned} \quad (6)$$

Modulus of Resilience = Energy absorbed and released during elastic deformation
= Area under the stress-strain curve up to yield strength

$$= \int_0^{\epsilon_y} \sigma d\epsilon = \frac{1}{2} \sigma_y \epsilon_y = \frac{1}{2} \sigma_y \left(\frac{\sigma_y}{E} \right) = \frac{\sigma_y^2}{2E} \quad (7)$$

The stress and strain used in Equations (1) to (7) are termed engineering stress and engineering strains when original gage length and original cross sectional area are used. In reality, the cross sectional area changes due to Poisson's effect continuously resulting in a somewhat different stress and strain during the test. For more realistic account of the real stress and strain, true stress and true strain may be calculated using Equations (8) and (9).

$$\text{True Stress } (\sigma_t) = \sigma (1 + \epsilon) \quad (8)$$

$$\text{True Strain } (\epsilon_t) = \ln(1 + \epsilon) \quad (9)$$

Using Equations (8) and (9), an engineering stress-strain curve may be converted to true stress-true strain curve. The segment of true stress-strain curve between true yield strength and true tensile strength can be described by a polynomial expression in the form

$$\sigma_t = K \epsilon_t^n \quad (10)$$

where the exponent n is *work hardening exponent* that describes the ease with which a metal can be work hardened (or strain hardened). The value of the work hardening exponent can be determined by solving two simultaneous equations from two arbitrary points on the true stress-strain curve between yield point and ultimate tensile point as

$$\text{Strain Hardening Exponent } (n) = \frac{\log\left(\frac{\sigma_{t1}}{\sigma_{t2}}\right)}{\log\left(\frac{\epsilon_{t1}}{\epsilon_{t2}}\right)} \quad (11)$$

Qtest/50 Universal Testing Machine

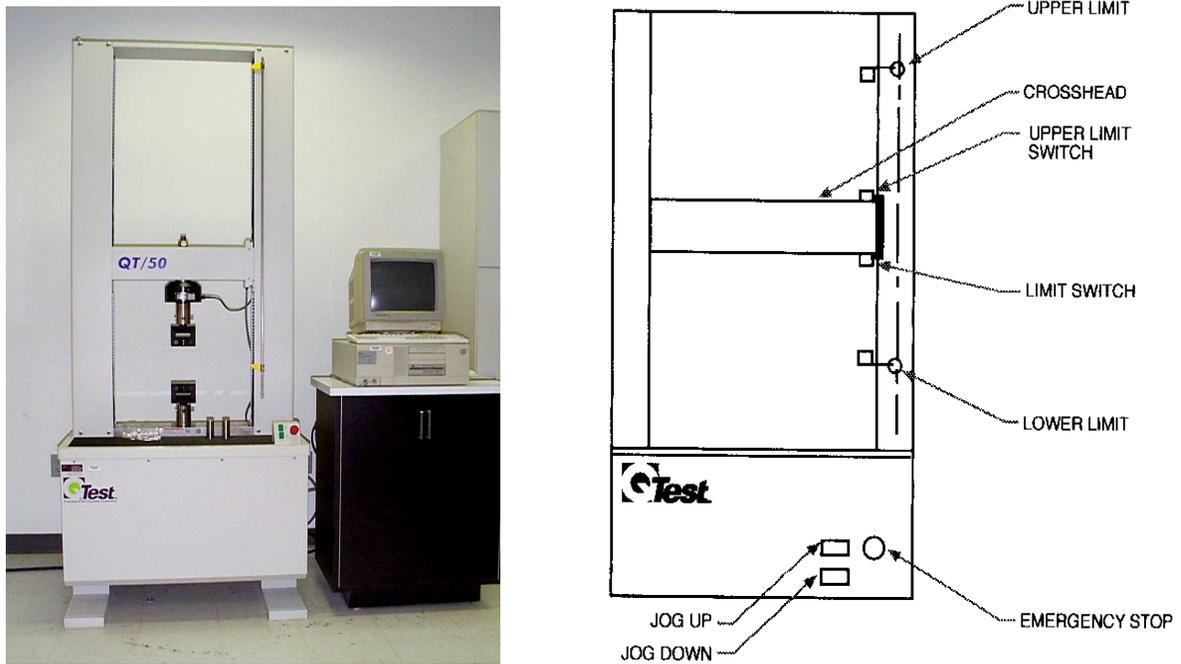


Figure 2 – (a) A Qtest/50 universal testing machine, (b) Important manual controls on the Qtest/50 universal testing machine.

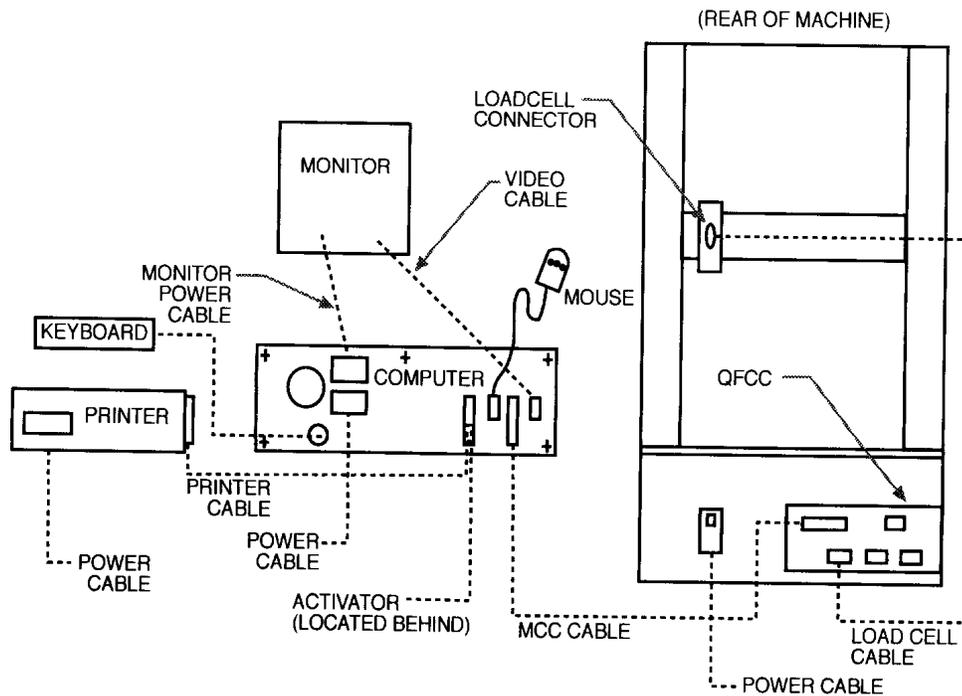


Figure 3 – The Qtest/50 UTM and control system.

Operating Procedure for Tensile Test on OTest/50

Follow the procedure carefully to avoid damages to the testing system and injury to the user. Read each step description entirely before executing a step. No students should be allowed to operate the system without faculty supervision in the laboratory.

1. Make sure you know where the *red emergency stop button* is located on the machine. Pressing the emergency stop button once will bring the machine to a quick stop. **DO NOT** press the emergency stop button a second time, unless really necessary, which may cause the crosshead to return rapidly to its starting position.
2. Install the correct type of sample grips. Make sure the connector pins are in place.
3. Turn on the testing system. **Always turn on the testing machine before the computer.** The toggle power switch is on the right side (lower right corner) of the machine.
4. Turn on the monitor and the computer in that order.
5. Measure dimensions of the sample: width, thickness (same as width for a bar sample), and gage length (axial length in which the diameter, width, or thickness is constant).
6. Double click on the **TestWorks QT v2.00** folder, then the **TestWorks QT2.02** icon to load the control program. A **User Login** window will appear.
7. Enter **MEM** for both User Name and Password, and click **OK**, or press **Enter**. Additional functions on the toolbar near the top of the screen are activated.
8. Click on the **Test** button. A new set of functions appears in the toolbar. Select the **Simple Tensile Test (English)** method from the drop-down menu for the Method. A load meter (**10000 lb cell**), a **Crosshead Position** meter and a **Handset** window appear.
9. Click on the **Calibrate** button on the toolbar. A small **Calibrate** window appears. Select **LOAD** from the sensor list and **10000 lb cell**.
10. Make sure only sample grips and fixtures (if any) are attached to the load cell, then click on the **Calibrate** button followed by the **OK** button. The automatic calibration starts and finishes in a few seconds.
11. Click on **OK** when the calibration is complete.
12. Click on **Exit** in the small Calibrate window to return to the Test window.
13. Click on **Sample** button on the toolbar. Enter a Sample ID for your sample and click **OK**. It is a good idea to have a sample ID that is short and self-explanatory.
14. Use the following procedure to install the specimen in the testing machine.
 - a) Screw one end of the specimen in the upper grip (assuming a rod sample is being used).
 - b) Remove the lower grip and screw it onto the lower end of the specimen.
 - c) Lower the sample (with the lower grip attached) to about ½ inches above the lower grip connector by pressing the green Jog Down button.

- d) In the Handset window, enter a speed of **2** (In/Min). Click on **Down** followed by **Stop** to lower the grip in to the connector while guiding the grip with hands. Insert the fastening pin when the holes are lined up.
 - e) Change the speed to an even slower speed (**0.01** In/Min) and adjust the crosshead position using **Up** (or **Down**) and **Stop** buttons to take out slacks, leaving the specimen under a small load (~**50** lb for metal samples, ~**10** lb for polymers).
 - f) Zero the **Crosshead Position** meter by clicking on the **Zero** button.
15. Click on **Inputs** button on the toolbar. An **Inputs** window appears.
- a) Select **Test** (under Category).
 - b) Click to highlight **Crosshead Speed** and enter an appropriate crosshead speed (consult Table 1 for suggested speed), highlight **Load Limit HI** and enter **8000** Lb, and highlight **Ext(ion) Limit HI** and enter **30.0** In.

Table 1 – Suggested crosshead speed for various materials. Note that the suggested speeds are not ASTM standard speeds. *These speeds are suggested so that a test may be finished in a reasonable length of time in a class period.*

Material	Crosshead Speed (In/Min)
Copper, Brass, Aluminum	0.03
Steel	0.02
Polypropylene	0.20
Rubber	1.00
High Density Polyethylene	1.50

- c) Select **Specimen** from Category and enter specimen dimensions.
 - d) Select **Calculation** category, enter sample gage length.
 - e) Select **Information**, enter information about the specimen material.
 - f) Click on **OK**, the **Inputs** window disappears.
16. Click on the **Window** button on the toolbar to bring up **Graphics Window**.
17. For Y-Axis Setup, click to select **Auto Scale Max**, **LOAD** form Channel 1 drop-down menu , **Lb** as unit for Y-Axis, **0** for Minimum, **500** for Maximum, and **0** for Decimals.
18. For X-Axis Setup, click to select **Auto Scale Max**, **EXTENSION** from Channel 1 drop-down menu, **In** as unit for X-Axis, **0.00** for Minimum, **0.05** for Maximum, **2** for Decimals, and **0.00** for X-Offset.
19. Click on **OK** to return to the **Test** window.
20. Click on **Run** button. A **Required Inputs** window appears. Enter correct gage length and click on the **Save/Next** button. Enter the same speed as that used in Inputs for crosshead speed and click **Save/Next** button. The **OK** button lights up.
21. Click on **OK** to start the test. A **Warning!** message appears.
22. Click on **OK** again to start. A separate **X-Y Curve** window appears showing the LOAD-vs.-EXTENSION data. The scales are programmed to change automatically with increasingly larger applied load and extension.

23. **Wait until the test is complete. Do Not** try to change crosshead speed during the test. **DO NOT** press the spacebar on the keyboard. Pressing the spacebar will cause the machine to terminate the test. Observe the “necking” phenomenon of the sample and relate it to the change in the curve shown in the X-Y Curve window.
24. Click on **File**. The **Test** window returns.
25. For polymer samples, unscrew the tightening screws in the grips and remove the sample. Go to step 28. For metal samples, go to step 26.
26. Use the green Jog Up button to move the crosshead upward to provide enough room for the removal of sample (broken pieces).
27. Remove both broken specimen pieces from grips.
28. Click on the **Exit** button to return to the main **TestWork QT** window.
29. Click on **Output** button. A listing of samples appears. Click to highlight your sample.
30. Click on the **Export** button to activate the **Export Options** window.
31. In the **Export Options** window, click to select **Curve**. Click **OK** to bring up the **Select Sample** window.
32. In the **Select Sample** window, enter sample ID and click **OK**. The sample ID should be identical to that on the list. Select sample **1** (the only one with your sample ID) and click **OK**. A **Select Channel** window appears.
33. In the **Select Channel** window, click to select **Extension** and **Load**. Click **OK**. A **Select Delimiter** window appears.
34. In the **Delimiter** window, select **Tab** and click **OK**. An **Enter Filename** window appears.
35. Insert a formatted 3¹/₂-inch floppy disk in drive *a* of the computer. In the space under **Enter Path/Filename** window, enter *a:\filename.xls* (DO NOT forget the .xls file extension) and click **OK**. It takes a few seconds to export the test data in Microsoft Excel spreadsheet file format to the disk in drive *a*.
36. After the data transfer is complete, click on **Cancel** to exit the **Export Options** window.
37. Click **Exit** to return to the main **TestWorks QT** window.
38. Click on **Exit** followed by **Yes** button to exit the program. It is a good idea to check the data files on a different computer to make sure they are complete before exiting the program.
39. Exit Windows.
40. Turn off the computer and the monitor in that order.
41. Turn off the machine. **Note: Always turn off the computer before the testing machine.**

Assignments:

1. Obtain samples from the instructor. Measure and record the initial dimensions of the samples.
2. Perform the tensile tests with the samples provided following the procedure described in the handout. Record the type of material and measure sample dimensions before any test. After each test, save the test data in Excel format (file name with extension .xls) for data reduction using Microsoft Excel spreadsheet.
3. For the metal sample, use Excel spreadsheet to plot an engineering stress-strain tensile behavior curve from the collected data and determine the following material properties:
 - a) modulus of elasticity,
 - b) 0.2% offset yield strength,
 - c) ultimate tensile strength,
 - d) fracture strength,
 - e) ductility in percent elongation and percent area reduction, and
 - f) modulus of resilience.
4. For the metal sample, plot a true stress-strain tensile behavior curve up to engineering ultimate tensile strength of the material and determine the expression ($\sigma_t = K\varepsilon_t^n$) that describes the strain hardening behavior. Note: the expression is valid only between yield strength and ultimate tensile strength.
5. For the polymer samples,
 - a. prepare an engineering stress-strain curve for each of the polymer samples and relate the changes in curves to the physical changes in the sample during the tensile testing, and
 - b. estimate the short-term modulus of elasticity of each material.
6. Describe the differences between the tensile behavior of the metal sample and that of polymer sample you had observed.

Impact Tests

Objectives:

1. Familiarize with methods for toughness measurement with impact tests.
2. Determine the effects of carbon content, alloying elements, and cold work on the energy absorption capability of steel.
3. Observe the effect of temperature on the energy absorption capability of steel.

Background:

Besides strength to handle static loads, materials that are subjected to dynamic loads (such as jolts or vibrations during earthquake) must also exhibit adequate toughness (ability to absorb energy) to survive the dynamic loads. In general, toughness is associated with high strength and good ductility. Strength or ductility alone does not significantly improve toughness. For example, the stronger a steel is the less ductile it is, and the lower its capability of absorbing the energy of an impact load without failure.

The area under the stress-strain curve can be shown to be proportional to the energy required to rupture the specimen in a tensile test. A material with high strength or good ductility does not necessarily have good toughness. Although the energy absorbing capability of a metal when slowly tested to failure in a static tensile test is not quantitatively comparable to the energy adsorbing capability of the same metal in an impact, a qualitative comparison can be made by comparing stress-strain curves.

Although toughness appears to be independent of the type of loading, the rate at which the energy is absorbed may markedly affect the behavior of a metal. Therefore, toughness measured from impact tests may not be the same as that obtained from static tests.

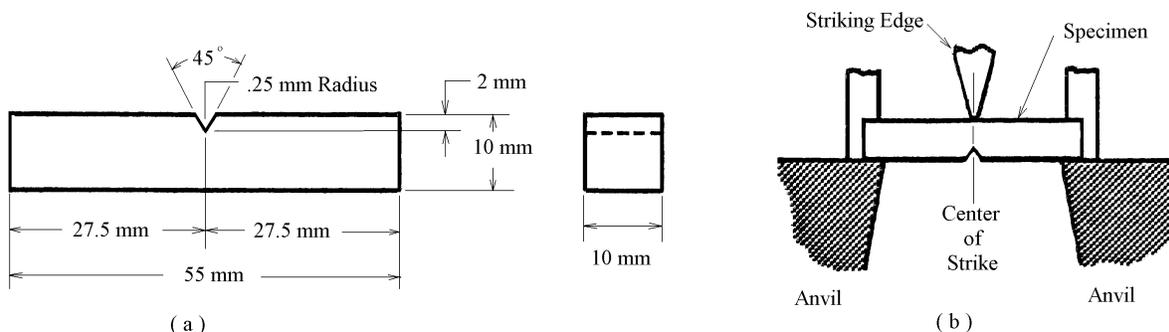


Figure 1 - (a) Specimen and (b) top view of loading method for Charpy impact test.

The most commonly used impact tests in the United States are Charpy and Izod tests. Both tests employ the pendulum principle where a swinging pendulum is allowed to fall and strike a specimen. These tests are made on small V-notched specimens of square cross section. The specimen is supported as a horizontal simple beam in Charpy tests (Figure 1), and is supported as a vertical cantilever in Izod tests (Figure 2). It should be observed that these tests do not, and are not intended to, simulate shock loading in service; they simply

measure the resistance to fracture of a particular notched specimen under a particular type of blow.

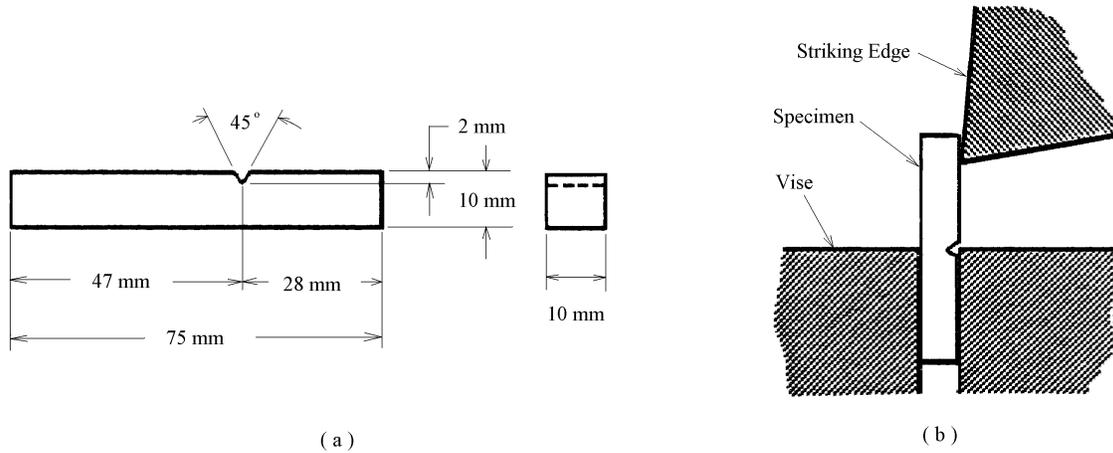


Figure 2 - (a) Specimen and (b) side view of loading method for Izod impact test.

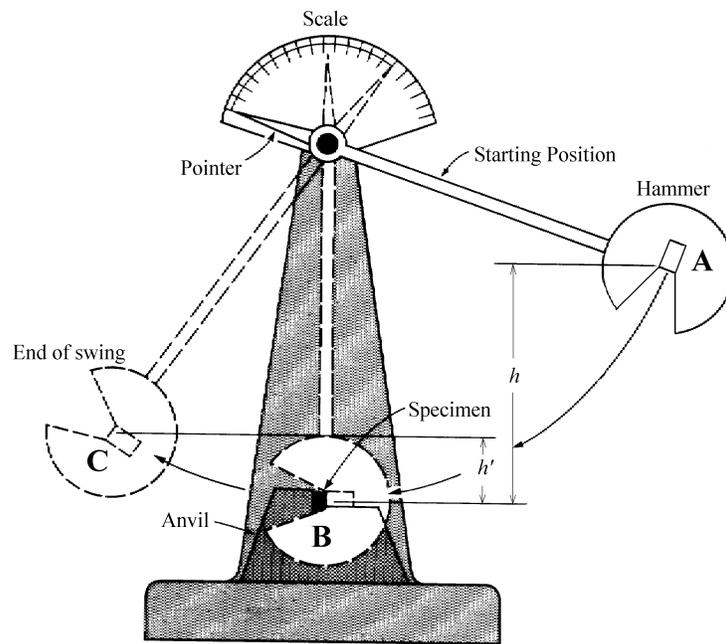


Figure 3 - Impact toughness testing machine that employs pendulum principle.

In impact tests, calculation of the energy required for fracture is of primary importance. It can be seen from Figure 3 that the pendulum's potential energy before release (point A) is mgh where m is the mass of the pendulum, g is the gravitational acceleration, and h is the initial vertical distance from the specimen to pendulum. Upon release, the potential energy decreases while the kinetic energy increases, until just before impact with the specimen (point B) the former is minimum and the latter maximum. During impact the amount of energy necessary to fracture the specimen is dissipated. As the pendulum continues its swing after

impact, the remaining kinetic energy is converted to potential energy. The potential energy is mgh when the pendulum reaches its farthest excursion at C. The difference between potential energy at A and that at C, $mg(h-h')$, is the impact toughness. In most tests, the toughness value is indicated by a friction pointer in the impact testing machine.

The toughness usually varies with temperature. At high temperatures a large absorbed energy is required to fracture the specimen, whereas at low temperatures the specimen ruptures with little absorbed energy. The results of a series of impact tests performed at various temperatures show the transition of ductile fracture (more energy absorption) to brittle fracture (little energy absorption) with decreasing temperature, Figure 4. The transition may be abrupt in a narrow temperature range for some metals, gradual over some appreciable temperature range for others.

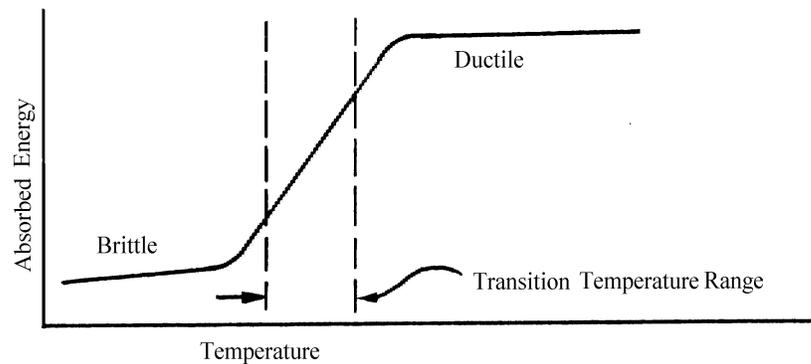


Figure 4 - Variation of impact toughness with temperature.

Another important property is the material's resistance to fracture in the presence of a flaw such as surface or internal crack. The resistance is termed *fracture toughness*. Fracture toughness is measured using precracked specimens subjected to increasing tensile load to cause the crack to propagate. Impact tests and fracture toughness tests are similar in that both use specimens with geometrical defects (V-notch and precracks) and stress concentration and extensive plastic deformation at the tips of V-notch and crack. Empirical relations have been developed to relate impact toughness to fracture toughness for steels in upper shelf (ductile) region:

$$\left(\frac{K_{IC}}{\sigma_y} \right)^2 = 5 \left[\frac{CVN}{\sigma_y} - 0.05 \right] \quad (1)$$

where K_{IC} is the plane strain fracture toughness ($ksi\sqrt{in}$), σ_y is the 0.2% offset yield strength (ksi), and CVN is the Charpy V-notch impact toughness (ft-lb). A good source for yield strength of materials is the web site www.matweb.com.

Procedure:

1. Calibrate the tester to account for bearing friction and aerodynamic drag of the pendulum by testing without specimen and adjusting the pointer to indicate zero toughness.
2. Raise and lock the pendulum at a selected upper position.
3. Zero the pointer.
4. Place a specimen in the tester. The notch should be on the side of the specimen farthest from the striking edge of the pendulum and directly in line with it.
5. Let the pendulum fall to rupture the specimen and observe the indicated energy value.

When the test is to be done at a temperature below ambient temperature:

1. The specimen is immersed in a liquid bath (alcohol) in a vacuum jar or an insulated beaker and cooled to desired temperature by the addition of small lumps of dry ice.
2. Specimens should be held at the desired temperature for at least five minutes. Temperature of the cooling bath can be measured by a thermocouple.
3. The test should be completed within five seconds after removal of the specimen from the cooling bath. No appreciable temperature changes occur within five seconds when alcohol is used.

Assignments:

1. Perform the impact test and determine the impact toughness of various types of samples. Record the material condition and test results on the datasheet.
2. Based on the test results identify the factors that have effects on the toughness of metals. In what way is the toughness changed by each of these factors?
3. For the ferrous metals, estimate the plane strain fracture toughness of the specimens from their CVN and yield strength. Present your calculation on a separate sheet of paper.

MECH 210 - Materials Science and Engineering Laboratory
Charpy V-Notch Impact Test

Date: _____

Name: _____

I. Charpy V-Notch Impact Test

Material	CVN (<i>ft·lb</i>) at _____°F (ambient temperature)	CVN (<i>ft·lb</i>) at _____°F (sub-zero temperature)	Yield Strength (<i>ksi</i>)	Plane Strain Fracture Toughness, K _{IC} (<i>ksi√in</i>)
1040 (Cold Drawn)		XXXXXX		
1040 (Hot Rolled)		XXXXXX		
1040 (Hot Rolled)	XXXXXX		XXXXXX	XXXXXX
4140 (Annealed)		XXXXXX		
4140 (Annealed)	XXXXXX		XXXXXX	XXXXXX
1020 (Cold Drawn)		XXXXXX		

Stress Concentration and Crack Propagation

Objectives:

1. Understand the occurrence of stress concentration at geometrical discontinuities.
2. Determine the stress concentration factor at a geometrical discontinuity.

Background:

A geometrical discontinuity in a body, such as a hole or a notch, results in a non-uniform stress distribution at the vicinity of the discontinuity. At some region near the discontinuity the stress will be higher than the average stress at distances removed from the discontinuity. Therefore, a stress concentration occurs at the geometrical discontinuity, or stress raiser.

The increased stress can be expressed by a stress concentration factor. The factor is described as the ratio of the maximum stress at the discontinuity to the nominal stress based on the net section:

$$K_t = \frac{\sigma_{\max}}{\sigma_{\text{nominal}}} \quad (1)$$

where K_t is the theoretical, or geometric, stress concentration factor based only on geometry without considering material effects. With material effects considered, the factor is known as effective stress concentration factor, K_e . The effective stress concentration factors can differ from theoretical factor because of such things as non-homogeneity due to different grain sizes or anisotropy.

By analyzing a large plate containing an elliptical hole, as shown in Figure 1, it has been shown that the uniform tensile stress, σ , is magnified at the end of the long axis of the ellipse by a factor estimated as

$$K_t = 1 + \frac{2a}{b} \quad (2)$$

where a is the half-width and b is the half-height. For a circular hole ($a = b$) the stress concentration factor is about 3. A very narrow hole, such as a crack with a much greater than b , normal to the tensile load can result in a very high stress concentration.

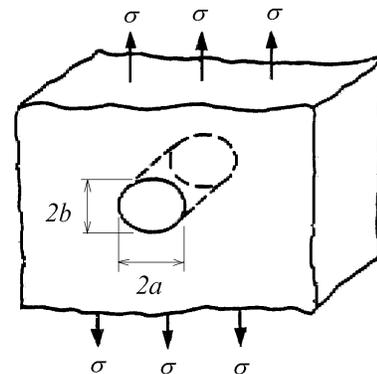


Figure 1 – A plate with a through-thickness hole under uniform tensile load.

Since actual machine components invariably contains stress raisers like fillets, keyways, screw threads, press fits, and holes, it is not surprising to find that cracks usually start at such geometrical irregularities. Stress concentration can also arise from surface roughness and metallurgical stress raisers such as porosity, inclusions, local overheating in grinding or decarburization. One of the best ways to reduce failure caused by stress concentration is by reduction of avoidable stress raisers through careful design, machining, and fabrication.

Figure 2 show the stress concentration factor (K_t) as a function of the central hole diameter (d) to the width of a flat plate (b) ratio under a uniaxial tensile load (P).

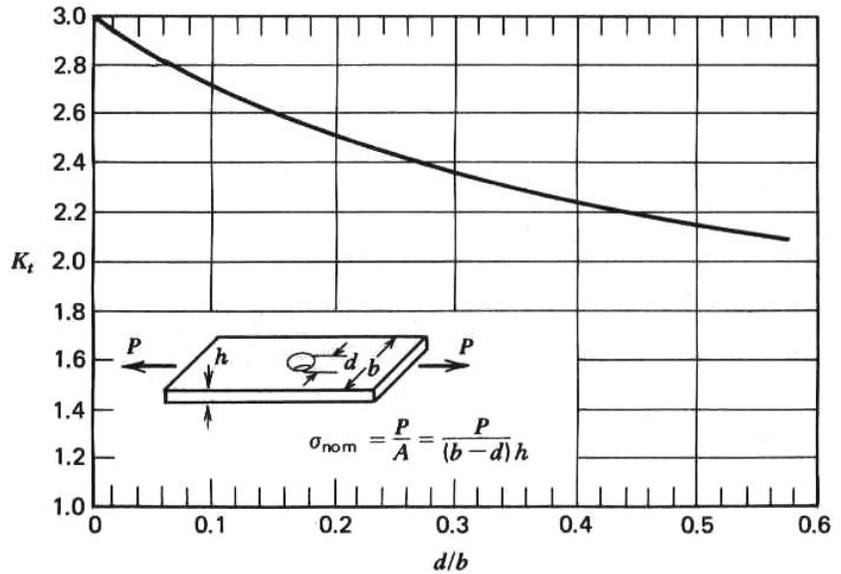


Figure 2 – Theoretical stress concentration factor for a flat plate with a central hole under a uniaxial tensile load.

For a plate containing a through hole similar to that shown in Figure 2, under uniaxial tensile stress, the stress magnitude from stress concentration varies inversely with the distance from the hole as shown in Figure 3. The ratio of the maximum stress, σ_{max} , to nominal stress, $\sigma_{nominal}$, is the stress concentration factor as estimated using the curve in Figure 2.

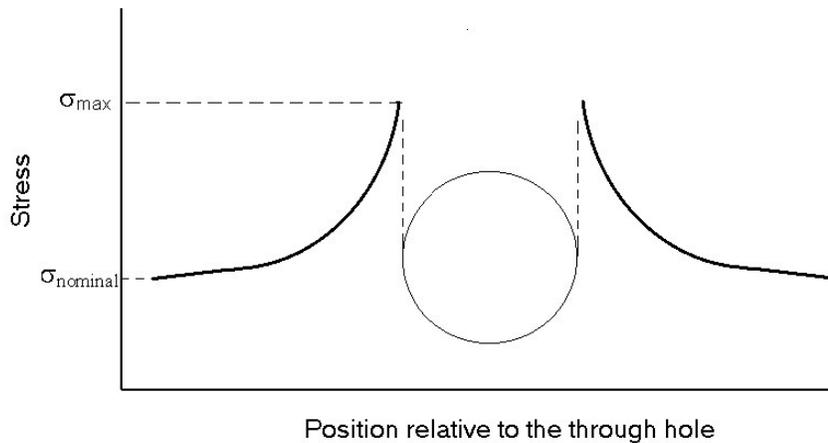


Figure 3 – The schematic stress profile near a through hole in a plate under tensile stress as shown in Figure 2.

Procedure:

A rubber specimen with a circular hole and a square grid of lines printed around the hole (Figure 4) is used. A rubber specimen is selected because the modulus of elasticity of rubber is low so that a small force can produce measurable deformation. The relationship between stress and strain within elastic range, however, is not linear for rubbers. Therefore, an average modulus of elasticity will be determined for the rubber.

1. Mark two fine points and measure a horizontal length l_1 at the edge of the circular hole and three additional locations at various distances from the hole along the vertical line AB.
2. Measure distances L_x and l_1 's on specimen. L_x will be used to determine average modulus of elasticity and l_1 's to determine local strains and stresses.
3. Attach a holder for weights to the left-hand edge of specimen.
4. Add weights in 2 kg increments, measure and record L_x and l_1 's after each addition of weights. The mass for the weight holder is 1 kg.
5. Observe the change in shape and dimensions of grids along the edge of the hole.
6. The weights added should not exceed 15 kg. Remove the weights as soon as the maximum weight is reached to avoid permanent damage to the specimen.
7. Calculate the average modulus of elasticity of the rubber from the slope of the stress-strain curve obtained at L_x .
8. Calculate local stresses at selected locations from local strains and average modulus of elasticity. Plot a stress profile to show the change of stress with increasing distance from the edge of the hole.

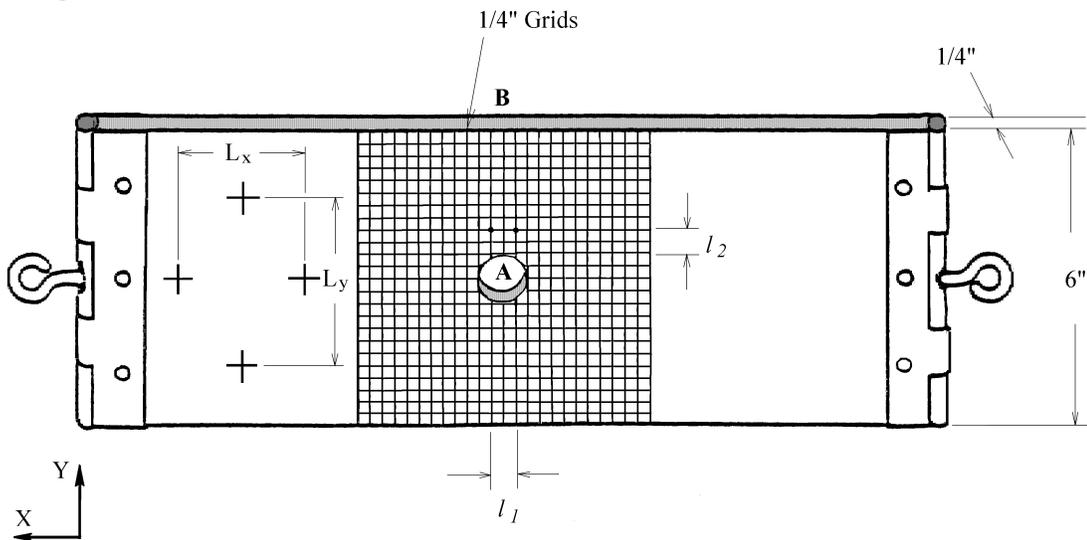


Figure 4 – Rubber sheet specimen.

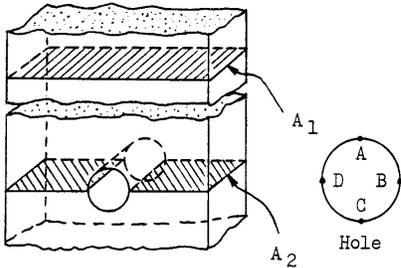
Assignments:

1. Measure sample dimensions under no-load condition and record results in the datasheet.
2. Increase the applied load to the sample in 2-kg increments. Record the loads and corresponding change in dimensions of the sample after each 2-kg addition in the datasheet.
3. Determine the average modulus of elasticity for the rubber specimen using stress and strain data in Section I of the datasheet. The modulus of elasticity is the slope of the best-fit straight line through data points on the stress-strain plot.
4. Determine the maximum stress concentration factor for the specimen with a circular hole.
5. Plot a stress profile (local stress versus distance from hole) near the through-thickness hole similar to that shown in Figure 3. Show stress magnitude and distance from the hole.
6. Although the specimen is under tensile stress in the experiment, did you observe any region near the hole under compression? Describe your observation, using the sketch of the specimen in data sheet if necessary.

MECH 210 – Materials Science and Engineering Laboratory
Stress Concentration Experiment

Date: _____

Name: _____



Specimen material: _____

Thickness: _____ mm

Width: _____ mm

Diameter of round hole: _____ mm

Total cross sectional area (A_1): _____ mm²

Net cross sectional area (A_2): _____ mm²

At a location away from the hole for the determination of elastic modulus

Load (kg)	Load (N)	Stress (MPa)	L_x (mm)	ΔL_x (mm)	Strain, ϵ_x
0	0	0		0	0
2					
4					
6					
8					
10					
12					

At various locations for the determination of stress concentration factor and stress profile

Distance from the edge of the circular hole, l_2 : _____ mm						
Load (kg)	Load (N)	Stress(MPa)	l_1 (mm)	Δl_1 (mm)	Strain, ϵ_1	Local Stress (MPa)
0	0	0		0	0	0
12						

Distance from the edge of the circular hole, l_2 : _____ mm						
Load (kg)	Load (N)	Stress(MPa)	l_1 (mm)	Δl_1 (mm)	Strain, ϵ_1	Local Stress (MPa)
0	0	0		0	0	0
12						

Distance from the edge of the circular hole, l_2 : _____ mm						
Load (kg)	Load (N)	Stress(MPa)	l_1 (mm)	Δl_1 (mm)	Strain, ϵ_1	Local Stress (MPa)
0	0	0		0	0	0
12						

Distance from the edge of the circular hole, l_2 : _____ mm						
Load (kg)	Load (N)	Stress(MPa)	l_1 (mm)	Δl_1 (mm)	Strain, ϵ_1	Local Stress (MPa)
0	0	0		0	0	0
12						

Computer Modeling of Stress Concentration, Crack Opening and Crack Propagation

Getting Ready

1. Turn on the computer (under the table), if not already running.
2. Enter user name and password, both should be your first initial followed by last name (in lower case with no space between them). Make sure the domain is MEM.
3. Wait until Windows screen appears, right click **Start**, left click **Explorer**. Double click the file **fracture** under [C:] to open.

Generate a Meshed Model

4. Double click **Casca.exe** to start the program. Answer the question:
Big window, or small (b, s): *s* and press **Enter** key
The GRA/X window now appears, with a 12×12 grid in it.
5. Click **Set Scale**, **Data Size**, and click to enter **10** and **ENT** on the numeric keypad in the lower-right corner of the window. It may be necessary to click on the title bar and move the CASCA window up a little to see the lower portion of the numeric keypad.
6. Click **Spacing XY** and enter **1.0** followed by **ENT** key. The grids are now 10 × 10 in the **GRA/X** window.
7. Click **RETURN**, **Grid**, **Geometry**. A new menu appears.
8. Click **Get Circle**.
 - (a) Click the point at 1 unit distance directly above the × sign (at the center of the grid) to use as a starting point for creating an arc.
 - (b) Click the point at 1 unit distance to the right of the × symbol to use as the ending point.
 - (c) Click the point at the × symbol as the circle center point.
 - (d) Click **DONE** to create a quarter circle.
9. Click **Get Circle**.
 - (a) Click the point at 1 unit distance to the right of the × symbol (ending point of previous quarter circle).
 - (b) Click the point at 1 unit distance below the × symbol.
 - (c) Click the point on the × symbol, and **DONE** to finish the second quarter circle.
10. Click **Lines Connect**.
11. Click the point at the top end of the now semi-circle as the starting point, click the point 3 squares directly above the starting point to connect the first line segment.
12. Click the point 4 squares to the right to connect the second line segment, click the point 8 squares down to connect the third line segment, click the point 4 squares left to connect the fourth line segment, click the point 3 squares up (at the bottom end of the semi-circle) to connect the fifth line segment.

The outline of half of the specimen model (4 in x 8 in with a semi-circular hole having a radius of 1 in) is created.

13. Click **Quit**, **RETURN**, **Subregions**, **Get Line**. Click the middle point on the right edge of the semi-circle and the point at 3 unit distance to the right (on the right boundary of model), and **DONE**. The model is now divided into two symmetrical halves (upper and lower halves).
14. Click **Get Line** and create a horizontal line at 2 squares above the previous dividing line, with ends on left and right boundaries. Click **DONE**.
15. Click **Get Line** and create another horizontal line 2 squares below the first dividing line, with end on right and left boundaries. Click **DONE**.

The model is now divided into four subregions.

16. Click **RETURN**, **Subdivide**, **No. of Segments**. (to subdivide the line segments for meshing)
17. Click to enter **10** and **ENT** (on the numeric keypad).

Click **Subdivide** and click on

- (a) each of the 2 quarter circles,
- (b) the 2 vertical line segments connected to the ends of the semi-circle, and
- (c) the horizontal line segment connected to the middle point of the semi-circle.

The line segments are divided into 10 equal divisions.

18. Click **QUIT**, **No. of Segments**, **5**, **ENT**, **Subdivide**. Click on all the remaining segments.
19. Click **Quit**, **RETURN**, **Mesh**.
20. Click the **Bilinear 4side** element type, and click anywhere inside the top subregion.
21. Mesh the remaining 3 subregions by sequentially selecting the **Bilinear 4side** element type and clicking anywhere in each subregion.

The model is now meshed.

22. Click **RETURN**, **Write Mesh**. (Create a file to save the meshed model) The program is waiting for you to activate the **CASCA** window.
23. Click any part of the smaller window (**CASCA** behind the current one) to activate it, and enter the mesh file name: **plate** and press **Enter** on keyboard. Wait until the message “Done writing file ...” appears.

If a different names is used, there should be no space in the name.

24. Click any part of the previous **GRA/X** window to return, and click **END**, **CONFIRM EXIT**. (To exit the program)

Analysis

25. Double click the file **franc2dl.exe** to open the **FRANC2DL** window.
26. Answer the questions in the window:

Filename: **plate** and press **Enter**

Restart (.wdb): 0, or New File (.inp): 1 : **I** and press **Enter** key

Big window, or small (b, s): **s** and press **Enter** key

A large window (Franc2D/L-Main) now appears with the meshed model.

27. Click **PRE-PROCESS, MATERIAL** (to input or modify material properties of the model)

A third window (Franc2D/L-Aux) appears showing all default material properties.

28. Click on the Franc2D/L-Main window to reactivate it.

*It is important now to drag the title bars and arrange the three windows in such a way that you can see and activate any of them when needed. **DO NOT** let any window disappear completely behind others.*

29. In the reactivated main window, click **E, 10, EEX, 6, ENT** (to enter 10E6 psi for modulus of elasticity E),

click **NU, 0.30, ENT** (to enter 0.3 for Poisson's ratio),

click **THICKNESS, 0.5, ENT** (to enter thickness = 0.5 in.),

click **KIC, 40, ENT** (to enter 40 ksi $\sqrt{\text{in}}$ for fracture toughness)

30. Click **RETURN, FIXITY, FIX EDGE, X**

31. Click on the node at the lower-left corner of the model, and the one just above it.

Use **Zoom+** to zoom in and click the corner node at the lower end of the semi-circle to apply fixity to the entire lower left boundary. (Displacement in x-direction is restricted.)

32. Click **FIX EDGE, X**. Click the corner node at the top end of the semi-circle, and the node right above it.

Use **-Zoom** to zoom out so you can see and click the node at the upper-left corner of the model to apply fixity. (Again, displacement in x-direction is restricted as indicated)

33. Click **FIX IND, Y**, and then the node at the right end of the center horizontal dividing line. (Displacement in y-direction is restricted for that particular node)

34. Click **RETURN, RETURN, LOADS, DIST LOAD, Y GLOBAL, CONSTANT**

35. On the upper edge, click sequentially the first node at the left end, the adjacent node, and then the last node at the right end.

Click to input **10000**, and **ENT**. (a stress of 10000 psi is applied in positive y-direction)

36. Click **DIST LOAD, Y GLOBAL, CONSTANT**

37. On the lower edge, click sequentially the first node at the left end, the adjacent node, and the last node at the right end.

Click to input **-10000** (Note: this is a *negative* stress in negative y-direction), and **ENT**. (a stress of 10000 psi is applied in *negative* y-direction)

38. Click **RETURN, RETURN, ANALYSIS, LINEAR, DIRECT STIFF**, and wait until the analysis is complete.

39. Click **RETURN, POST-PROCESS, CONTOUR, STRESS, SIG Y** to plot the stress contour for y-stress. The color chart for stress levels can be seen in the Franc2D/L-Aux window.

** Answer Problem No. 1 in the report before proceeding to the next step.*

40. Click **RETURN, RETURN, RETURN, WRITE FILE**, the program is waiting for you to activate the FRANC2DL window.

41. Click any part of the FRANC2DL window (behind the current one) to activate, enter **plate1** as the checkpoint file name, and press **Enter**. The model with boundary conditions and analysis results is now saved.

42. Click any part of the Franc2D/L-Main window to return.

Crack Initiation

43. Click **MODIFY, NEW CRACK, NON-COHESIVE, EDGE CRACK**

44. Zoom in on the right edge of the semi-circle and click the node where the y-stress is the highest. Click **DONE**. (The node is where the crack is expected to initiate)

45. Counting the node on the edge of the hole as the first node, click on the third node (on the same horizontal line).

46. Specify minimum number of elements along the crack extension by click to input **2, ENT**. Some elements are deleted in that region.

47. Click once anywhere in the Franc2D/L-Main window, a crack is inserted.

Click again in the Franc2D/L-Main window, elements are inserted at crack tip.

Click again in the Franc2D/L-Main window, elements are inserted around the new crack.

Click **ACCEPT** to include these new elements and update the program data structure.

48. Click **RETURN, ANALYSIS, LINEAR, DIRECT STIFF**, wait until the analysis is completed.

49. Click **RETURN, POST-PROCESS, DEFORMED MESH** to see crack opening.

50. Click **RETURN, CONTOUR, STRESS, SIG Y** to see stress contour plot.

** Answer Problem No. 2 in the report.*

51. Click **RETURN, RETURN, RETURN, WRITE FILE**, click to activate the FRANC2DL window, and enter file name **plate2**, and press **ENTER** to save the checkpoint file.

52. Click the Franc2D/L-Main window to return,

53. Click **POST-PROCESS, FRACT MECH, MD CRK-CLOS**.

Activate the Franc2D/L-Aux window to find maximum stress intensity factor (KI).

** Answer Problem No. 3 in the report.*

Crack Propagation

54. Click anywhere in the Franc2D/L-Main window to return to the main window.

55. Click **RETURN**, **RETURN**, **MODIFY**, **MOVE CRACK**, **AUTOMATIC**, **CRACK INCR**, and click to input **0.10** and **ENT**. (Crack propagation at 0.10-in. increments)
56. Click **STEPS** and input **5**, **ENT**. (Crack extension in 5 steps of 0.10 in each)
57. Click **PROPAGATE**
 Propagation of the crack occurs in 5 steps. For each step, the program remeshes the crack tip region and performs stress analysis. The calculation status report can be seen in Franc2DL window. Wait until the steps are finished. This will take a few minutes.
57. In the main Franc2D/L-Main window, click **RETURN**, **POST-PROCESS**, **DEFORMED MESH** to view cracked geometry.
58. Click **RETURN**, **CONTOUR**, **STRESS**, **SIG Y** to see the stress plot.

*** Answer Problem No. 4 in the report.**

Fatigue Crack Growth Analysis Results

59. Click **RETURN**, **RETURN**, **RETURN**, **WRITE FILE**, click to activate the FRANC2DL window, and enter file name *plate3* and press **Enter** key to save the checkpoint file.
60. Click the FRANC2D/L-Main window to return,
 click **POST-PROCESS**, **FRACT MECH**, **SIF HISTORY**, **KI**
61. The KI (mode I stress intensity factor) vs. crack length diagram is shown in Franc2D/L-Aux window.
 Click **RETURN**, **FATIGUE PLTS**
 Click **SET C**, and click to input **2E-12**, **ENT**
 Click **SET m**, and click to input **1.3**, **ENT** [The *C* and *m* are constants in the Paris equation, $da/dN = C(\Delta K)^m$, which can be used to calculate the number of stress cycles for crack growth]
 Click **CYCLE PLOT** for fatigue cycles-crack length diagram in Franc2D/L-Aux window.

*** Answer Problem No. 5 in the report.**

(For KI values perform step no. 60, for fatigue cycles perform step no. 61.)

62. Congratulations! You've made it. Now, click **RETURN** repeatedly, then **END**, and **CONFIRM** to exit the program. Don't forget to **delete data files!**

Delete Data Files and Log Out

63. Delete all your data files by selecting the file and press **Delete**, leaving only the following seven (7) executable files: cas, franc, manual, Casca, Casca_fr, Casca_ge, and Franc2dl.
64. Click the X button in the upper right corner to exit the Explorer.
65. Select **Start**, **Shut Down**, select the last option and **Yes** to log out.

Assignments:

1. Follow the procedure and finish the simulation exercise. Record data as necessary for the questions in the report.
2. Submit the question and calculation sheets with data, calculation, and results.

MECH 210 - Materials Science and Engineering Laboratory
Computer Simulation of Stress Concentration and Crack Propagation

Date: _____

Name: _____

1. Answer the following questions.

(a) Determine the d/b ratio where d is the hole diameter and b is the width of the plate model. Note: our computer model is only half of the whole model.

(b) Using the curve in Figure 2, estimate the theoretical stress concentration factor for the plate with a d/b ratio calculated in part (a).

(c) Determine the highest stress concentration factor using the stress contour plot in the Franc2D/L-Main window. The average stress (of the highest and the lowest stresses for the same stress range) for the largest area in same color may be used as the nominal (applied) stress. Data from simulation: average maximum local stress _____ *psi*, average nominal stress _____ *psi*.

2. For the edge crack (length 0.3 *in*) just introduced, estimate the stress concentration factor at the crack tip. Again, use the average stress level for the largest area as applied stress in calculation. Data from simulation: average maximum local stress _____ *psi*, average nominal stress _____ *psi*.

3. Answer the following questions:

(a) What is the Mode I stress intensity factor (KI in $psi\sqrt{in}$) for the crack just introduced?

(b) Estimate the geometry correction factor (Y) for the crack (length 0.3 *in*). Note: the applied stress is 10,000 *psi*.

4. Do you see any unusual stress distribution after the crack propagation? Describe what you think is unusual.

5. Answer the following questions.

(a) What is the current Mode I stress intensity factor, K_I ? (Follow procedure step 53 to bring up the Franc2D/L-Aux window to find K_I value.) Estimate the geometric correction factor (Y) for the current crack length of 0.8 *in* ($= 0.3 + 0.1 \times 5$). The applied stress is 10,000 *psi*.

(b) Based on the simulation results, how many stress cycles did it take to propagate the crack from a length of 0.6 *in* to 0.8 *in*?

(c) Calculate the number of stress cycles for the crack to propagate from 0.6 in to 0.8 in using Paris equation, $da/dN = C(\Delta K)^m$ in procedure step No. 61, assuming Y is a constant calculated in part (a). Note: the C and m values used in this simulation are the A and m values, respectively, used in our lectures.

(d) Compare the results from parts (b) and (c). If they are quite different (more than 20% different), explain why.

Strain Hardening

Objectives:

1. Observe and learn about the strain hardening effect in metals.
2. Learn to quantify cold work and its effect on material properties.
3. Generate a cold work vs. hardness curve to tailor strength of metals.

Background:

One of the most valuable properties of metals is that they can be “worked” into a desired shape during manufacturing processes such as rolling, forging, extrusion, stamping, etc. In these processes, a metal is deformed under a stress beyond its elastic limit. The metal is said to have been plastically (permanently) deformed. Also in these processes many properties of the metal can be modified by a proper combination of processing steps and parameters such as amounts of deformation and processing temperature.

When it is carried out at a temperature that is low relative to the metal’s melting temperature (lower than approximately one-half of the absolute melting temperature) the plastic deformation is termed “cold work”. The cold work, calculated as the percent reduction of cross sectional area, usually brings about changes in grain structure and material properties. In general, the metal becomes harder but less ductile. Both yield and tensile strengths of the metal also increase with increasing hardness. The toughness, however, decreases with the introduction of cold work. Other properties such as electrical conductivity and corrosion resistance are also changed. The phenomenon is termed strain hardening (or work hardening).

During cold work the grain structure is distorted while a fraction of the energy consumed in deforming the metal is stored in the form of strain energy in the metal. The strain energy is associated with the tensile and compressive zones around dislocations generated during cold work. The stored strain energy acts as the driving force for recovery and recrystallization (in that sequence) when the metal is subsequently subjected to a raised temperature. During crystallization the properties that have been altered during cold work are largely restored to their pre-cold-worked state; that is, the metal becomes softer, weaker, yet more ductile. Recrystallization is the formation of new grains free of stress and strain at the expense of the old grains.

The simplest method of measuring the changes in mechanical properties is with hardness testing because hardness can be correlated with many other properties. It is also possible to correlate results from different types of hardness measurement. Therefore, hardness measurement is used in this experiment to monitor changes in mechanical properties with amount of cold work in strain hardening.

A hand-rolling machine (Figure 1) is used to roll coupon samples at room temperature in this experiment. The amount of cold work is accomplished by changing the sample’s thickness, which is controlled by the gap between the rolls of the rolling machine.

The amount of cold work can be calculated in percent cold reduction in thickness (Equation (1)) or in percent reduction in cross sectional area (Equation (2)). The percent cold

reduction in thickness is typically used in rolling process while the percent reduction in area is used in drawing or swaging process.

$$\text{Percent cold reduction in thickness} = \frac{t_o - t_i}{t_o} \times 100 \quad (1)$$

$$\text{Percent reduction in area} = \frac{A_o - A_i}{A_o} \times 100 \quad (2)$$

In equations (1) and (2), t_o and A_o are initial thickness and cross sectional area, respectively, while t_i and A_i are instantaneous thickness and cross sectional area, respectively.



(a)



(b)

Figure 1 – (a) A hand-rolling machine used for cold work in this experiment. (b) One of the two index plates for the adjustment of rolling thickness.

Operating Procedure for Rolling Machine:

1. Measure the average thickness of the coupon sample.
2. Mark one end and part of a surface at the same end with a permanent marker for identification of rolling direction. The rolling direction is controlled with the marked end entering first and the marked face up in every rolling pass.
3. Check to make sure the pointers point to the same number on the index plates at both ends of the rolls. If the pointers point to different numbers (gap may not be consistent along the length of the rolls), notify the instructor for proper alignment of the rolls.

4. The gap between rolls can be increased by turning the handle bar clockwise, reduced by turning the handle bar counterclockwise.
5. With a gap between rolls about the same as the sample thickness, try to push the sample through the gap between rolls. If the sample goes through (gap is too large), turn the handle bar counterclockwise slowly to reduce the gap until the rolls pinch the sample while it is being pulled out. Otherwise, turn the handle bar clockwise to increase the gap until the sample can be pushed through.
6. Take note of the number at the pointer on the index plates.
7. Reduce the gap by one numbered division and roll the sample once.
8. The sample thickness can be further reduced by rolling with reduced gap between rolls. The reduction in gap setting should be no greater than two numbered divisions in each pass. A large thickness reduction can be achieved through consecutive passes with decreased gap in each pass.
9. Always take note of the gap setting before leaving the rolling machine for hardness measurement. The correct gap for follow-up rolling can be easily regained by turning the handle bar for the recorded setting.

Assignments:

Two specimens (specimens no.1 and 2) of the same composition and processing history are provided for the following assignments.

1. Estimate the initial tensile strength of the specimen material from its hardness.
2. Use specimen no. 1 to generate a hardness-percent thickness reduction curve.
3. Determine a point on the hardness-percent thickness reduction curve that can be referenced to improve tensile strength of the material by 50%. The curve and the reference point will be used for strain hardening of the material (specimen no. 2).
4. Cold work specimen no. 2 to the desired thickness determined from the reference point on the control curve to improve the tensile strength of specimen by 50% .
5. Indicate the experiment data point corresponding to the final thickness and tensile strength on the hardness-percent thickness reduction diagram.
6. Include the control curve along with the reference point and the experiment data point in the report.

Specimen Preparation and Microscopic Examination

Objectives:

1. Familiarization with the procedure for preparation of a material specimen for microscopic examination.
2. Familiarization with compound optical microscopes and metallography.
3. Examination of surface characteristics of engineering materials.
4. Grain size determination of metals.

Background:

The preparation of a metallurgical specimen generally can be divided into a series of stages: sectioning, mounting, grinding and polishing, and etching.

Sectioning

Sectioning is the removal of a small representative volume of material from the parent piece. The microstructure of the material must not be altered in the process. Cold work and heat are the two most likely conditions that can quickly bring about structure changes. Quite obviously operations such as sawing that generates heat or shearing that introduces cold work are not preferable for sectioning. Cutting using a bonded abrasive wheel with coolant offers the best solution to minimize or eliminate heat and deformation.

Mounting

Metallurgical specimens are mounted primarily for (1) convenience in handling and (2) protection and preservation during subsequent grinding and polishing. Two methods are frequently used: compression mounting and cold mounting.

Compression mounting is done by mounting the specimen in a cylinder of hard polymer under pressure and elevated temperature in a molding machine (Figure 1). The method is often preferred when speed and a relatively hard mounting is required. For metallurgical examination, specimens are usually molded in cylinders 1, 1¹/₄, or 1¹/₂ inches in diameter.

Compression molding materials are (1) thermosetting or (2) thermoplastic polymers. Bakelite and diallyl phthalate fall into the first category while transoptical material into the second. By definition, thermosetting materials require heat and pressure during the molding cycle, and therefore may be ejected at high molding temperature. Transoptical materials remain molten at high temperature and become transparent with increasing pressure and decreasing temperature.

Molding pressure, temperature, and time duration are the major variables involved in compression mounting. By equipment design, temperature may be held constant leaving pressure and time duration as variables.

Cold mounting is done by placing the specimen at the center of a metal or pyrex ring on a glass plate and pouring liquid mounting material into the ring to cover the specimen. Allow

the mounting material to cure at room temperature for 60 to 90 minutes before removing the ring. The method offers particular advantages when a specimen is too delicate to withstand the pressure and heat involved in compression molding. With cold mounting, large groups of specimens may be easily prepared in a short time.

Common types of cold mounting material include (1) epoxides (2) polyesters and (3) acrylics. These materials are two-component types consisting of a resin and a hardener. Since the curing process (polymerization) is an exothermic reaction the mixing by volume or weight ratios of each type is critical.

Grinding and Polish

Grinding and polish are accomplished by sequential coarse grinding, medium grinding, and rough and final polishing. The specimen should be carefully rinsed before proceeding from one operation to the next.

Coarse grinding is done on a wet-belt grinder with 120 and 240 grit belts. The purpose of coarse grinding is to obtain a flat surface free from previous cutting tool marks.

Medium grinding is accomplished using successively finer grits of metallographic grinding paper. The paper is supported on a hard, flat surface such as glass or steel. The specimen is moved along the length of grinding paper without rotation or a rocking motion. When grinding is completed on one grit the scratches should all run in the same direction. Before proceeding to the next finer grit the specimen should be washed to avoid bringing large particles to the finer grit. The specimen is rotated 90 degrees between grits so that scratches from each successively finer grit run at right angles to those from the previous one. The polishing on a grit is complete when coarser scratches from previous grit have been totally removed.

Rough and final polishing is accomplished on cloth-covered wheels charged with fine abrasive alumina particles suspended in water. Nylon cloth and 1.0- μm alumina particle size are used for the rough polish; a velvet cloth and 0.05- μm particle size for the final polish. A few drops of water are added to the rotating wheel to improve polishing action and cleanliness. Initially the specimen is held at one position on the wheel, without rotation, until most of the previous grinding marks are removed. The specimen can then be rotated slowly, counter to the wheel rotation, until only scratches from the alumina are visible. The final polish should be completed at a slow speed on a different polishing wheel.

Etching

The specimen surface is fairly smooth immediately after the final polish. A smooth surface deflects lights from the illuminator in the metallurgical microscope along the same direction showing no contrast and cannot reveal surface characteristics. Surface characteristics such as different phases, inclusions, porosity, cracks, intergranular corrosion can be revealed by etching. Etching is defined as the process to reveal structural details by preferential attack of a metal surface with an acid or other chemical solutions.

Experimental Procedure:

1. Obtain a steel specimen from the instructor and remove as much surface scale as possible. The steel specimen has been heat treated to form a desired structure for this exercise.
2. Mount the specimen in a phenolic cylinder using a compression mounting press. Watch carefully the demonstration of the use of compression mounting press. Appropriate molding pressure and time should be used in the process.

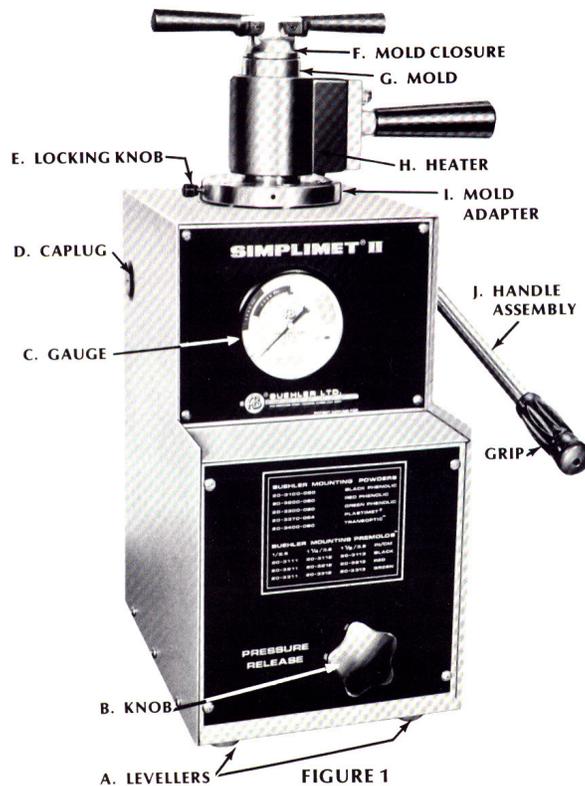


Figure 1 – A compression mounting press.

3. Prepare the specimen by coarse grinding on a wet-belt grinder, hand polishing on four successively finer grits of polishing paper, and fine polishing on two polishing wheels with 1.0- μm and 0.05- μm alumina powders. Rinse the specimen thoroughly between steps.
4. Etch the steel specimen by immersing it in a nital solution (5% concentrated nitric acid in alcohol). Start with 5 seconds of immersion. Rinse the specimen with water, dry with paper towel, immerse briefly in alcohol, and blow dry the specimen with a blow dryer.
5. Examine the specimen under microscope and identify the surface features. The specimen surface may be overetched or underetched. An overetched specimen surface shows patches of dark color with no identifiable features. On the other hand, a shiny, smooth surface with little or no surface features revealed indicates an underetch. Repeat the final

polishing to remove the damaged surface and etching for less time if the specimen is overetched. In the case of underetch, repeat the etching step to enhance the contrast.

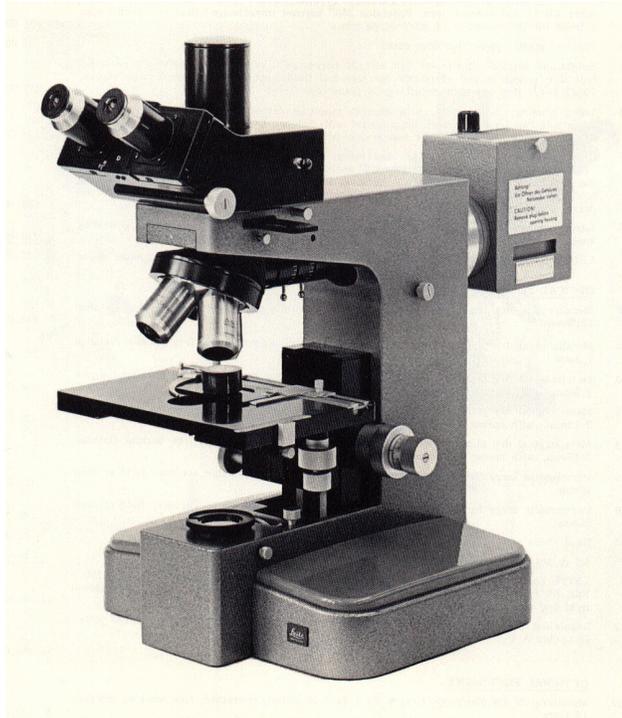


Figure 2 – A metallurgical microscope.

Microscope Focusing Procedure

1. Initially the lowest power objective lens is used for focusing the specimen. Turn the lowest-power objective lens into place. If necessary, turn the coarse stage height control to lower the sample stage to make room so the objective lens can be turned into place.
2. Turn the stage height focusing control to position the specimen about half a centimeter under the objective lens.
3. Look through the eyepieces and use the focusing controls (coarse and fine stage height controls) to bring the specimen into appropriate focus.
4. Scan the specimen surface by moving the stage using the stage position controls and select the areas that may warrant more complete study at higher magnification.
5. Turn the higher-power objective into place.
6. Adjust the stage height using the fine control until the specimen comes into sharp focus. Be sure that the objective lens does not touch the specimen surface at any time. Otherwise the objective lens may be scratched and permanently damaged.
7. A drop of oil on specimen surface usually is needed at higher magnification (greater than X2000) to help with focusing.

Photographing Microstructure

A Polaroid Land camera mounted on the Bausch & Lomb microscope is to be used to photograph specimen surface characteristics.

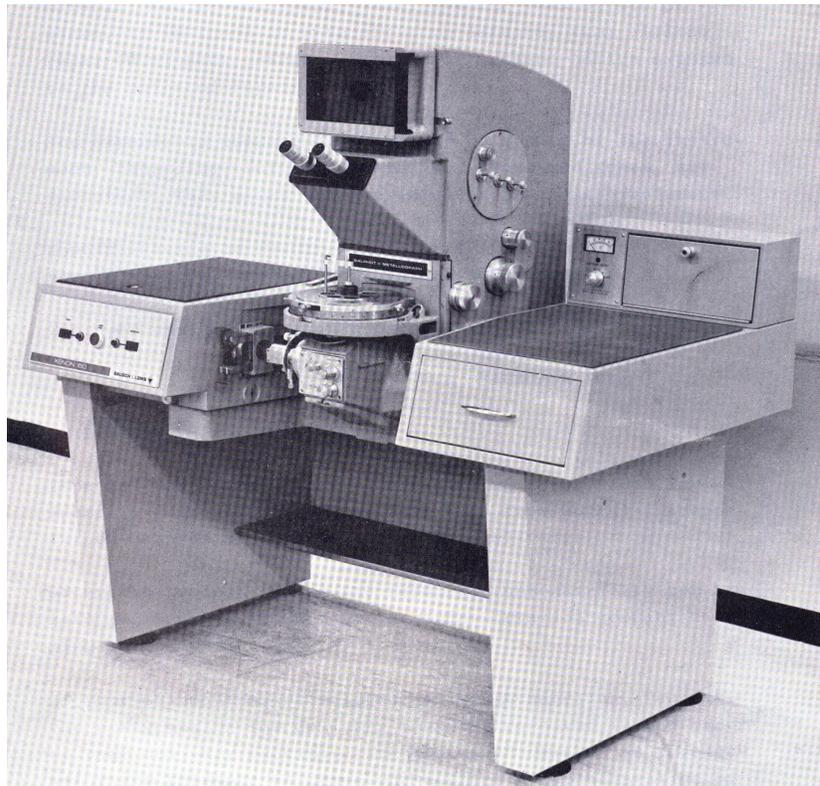


Figure 3 – A Bausch & Lomb microscope equipped with a Polaroid Land camera.

Procedure for photographing

1. Place the sample (inverted) on sample stage and bring the sample surface into focus at the desired magnification. Place a drop of oil at the center of sample to enhance focusing, if needed.
2. Check the Polaroid camera to ensure there are instant films in it.
3. Turn the visual observation knob clockwise to PHOTO.
4. Set the Shutter Speed with the Shutter Speed Control. Ask the instructor for the appropriate shutter speed.
5. Press the COCK OR CLOSE button.
6. Press the Release button.
7. Pull the exposed film envelop out of the camera and time the development before removing the photograph. Development time can be determined from the information sheet that comes with the film.

Assignments:

1. Watch the demonstration of specimen preparation and microscope operation procedures carefully.
2. Obtain a sample from the instructor and prepare the sample for microscopic examination following the procedure of mounting, grinding, polishing, etching, observation under a microscope, and photographing.
3. Keep a hard copy (photograph) of the sample as observed under the microscope. Record important information such as sample material, processing history, and photo magnification on the back of the photograph.
4. Include the photograph in the report and identify all the features observed.
5. Determine the ASTM grain size using the photograph. Show the measurement and calculation in the report.
6. Determine the Vickers microhardness of pearlite and ferrite in the specimen. Show the data in the report.

Jominy End-Quench Hardenability Test

Objectives:

1. Obtain hardenability curves for carbon steels.
2. Observe the effects of carbon content and alloying.
3. Associate the hardness and grain structure as observed under microscope.

Background:

The Jominy end-quench test is a laboratory procedure for measuring the hardenability of a given sample of steel. The standard specimen is a cylindrical bar with a 1-in diameter and 4-in length and a 1/16-in flange at one end. The specimen is first heat treated to contain only austenite (γ) phase. The austenitized sample is then placed in a quench tank and its lower end quenched with a jet of water as shown in Figure 1. With the sample in place, the distance from the specimen to the water jet nozzle should be 1/2 in. The height of the unimpeded water jet should be 2 1/2 in at 24°C from the nozzle of inside diameter 1/2 in.

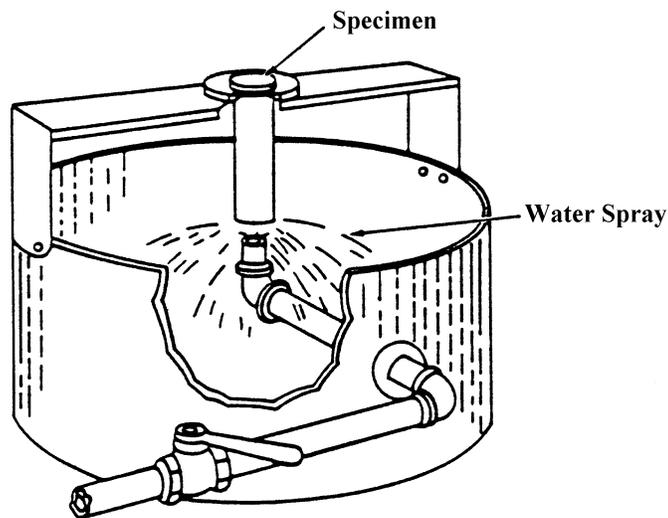


Figure 1 - Schematic illustration of the setup for Jominy end-quench hardenability test.

The quenched end cools rapidly while regions away from the quenched end cool at rates inversely proportional to their distances from the quenched end. The cooling rate varies from a high rate of approximately 600°C/s at the quenched end to approximately 3° C/s at the other end. Corresponding to the wide range of cooling rate is a wide range of types of transformation for the austenite. Martensite is the usual product at the quenched end, and bainite and pearlite increase in amount toward the slowly cooled end of the specimen. Measurement of hardness on a flat surface ground along the length of the quenched specimen gives an indication of these structures. A plot of the hardness versus distance from the quenched end (called Jominy distance, D_{qe}) is the hardenability curve

for the specimen steel. Figure 2 shows hardenability curves for several common grades of steels.

The hardenability of steels may be affected by factors such as carbon content, alloying, and grain size as observed in Figure 2.

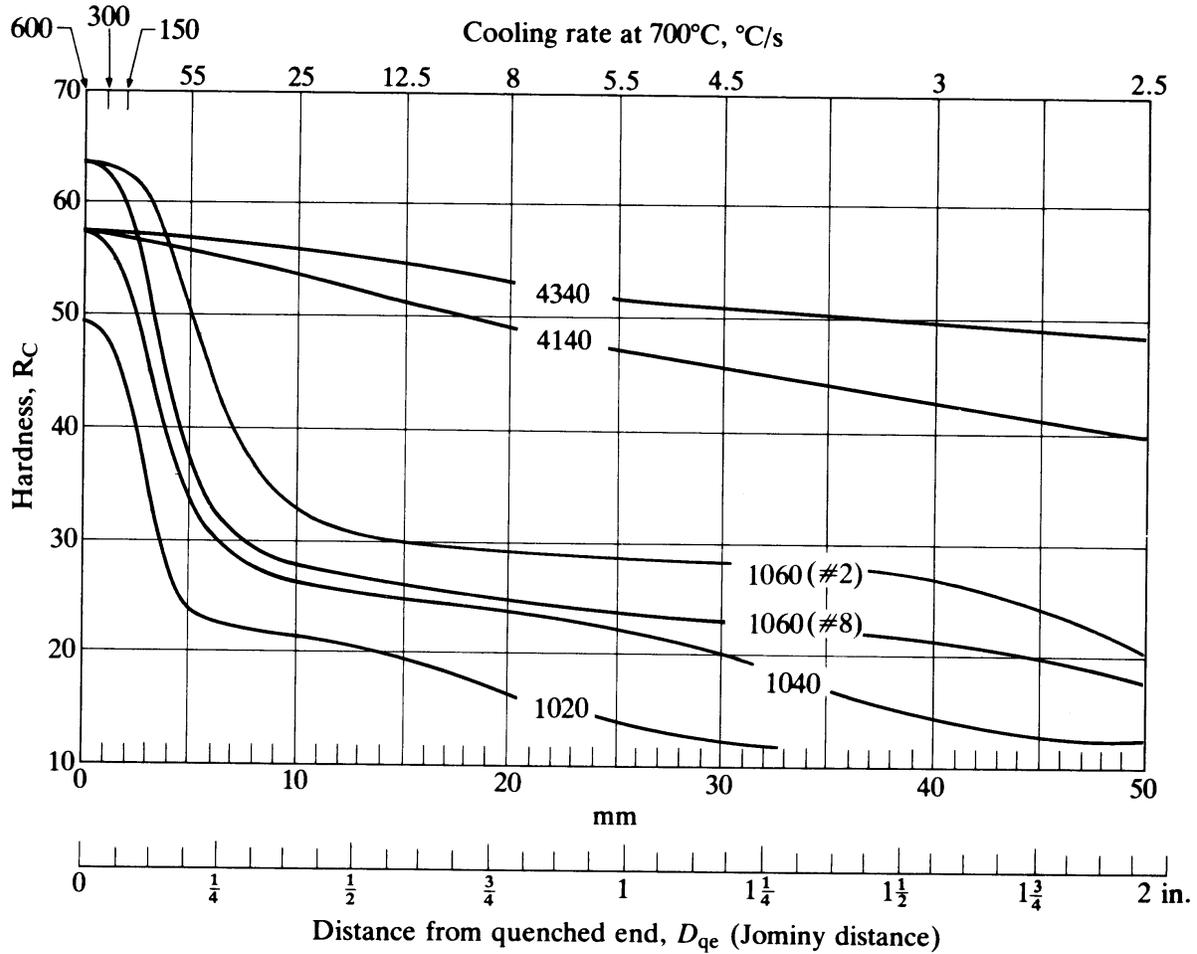


Figure 2 - Hardenability curves for steels of various composition and grain sizes.

A pure iron containing no carbon cannot be hardened by heat treatment. With increasing carbon content the martensite obtained by adequate quenching increases in hardness. Therefore, the hardness at the quenched end ($D_{qe} = 0$) is determined by the carbon content of the steel as shown in Figure 2. With alloying, alloy steels (4340 and 4140) generally have improved hardenability and maintain rather flat hardenability curves. Plain carbon steels (1060, 1040 and 1020) have curves that drop off quickly. Grain size refinement in general causes decrease in hardenability.

Procedure:

1. Heat treat the specimen in a furnace at a temperature above A_3 or A_{cm} for about an hour in a clay crucible filled with powdered charcoal to reduce decarburization.
2. Adjust the free water jet in the quench tank to a height of 2 1/2 inches, keep the specimen support dry.
3. Remove the specimen from furnace and place it in the quench fixture, open the quick opening valve immediately to allow the water jet to quench the lower end of the specimen.
4. Allow the end-quench to continue for a minimum of 10 minutes, then remove the specimen from the quench tank and cool it in running water.
5. Grind and polish a strip of flat surface of 1/4 in width along the length of the specimen, on opposite sides of the specimen.
6. Mount the specimen in a special fixture for accurate spacing of hardness tests. Make and record a series of hardness tests at specified locations on the flat surface.
7. Grind, polish, and etch the flat surface on specimen for microscopic examination.

Assignments:

1. Obtain samples from the instructor. The samples should be austenitized and ready for test.
2. Perform Jominy end quench test on the samples and record results on the datasheet.
3. Answer questions in the datasheet with appropriate graph.

MECH 210 – Materials Science and Engineering Laboratory
Jominy Hardenability Test

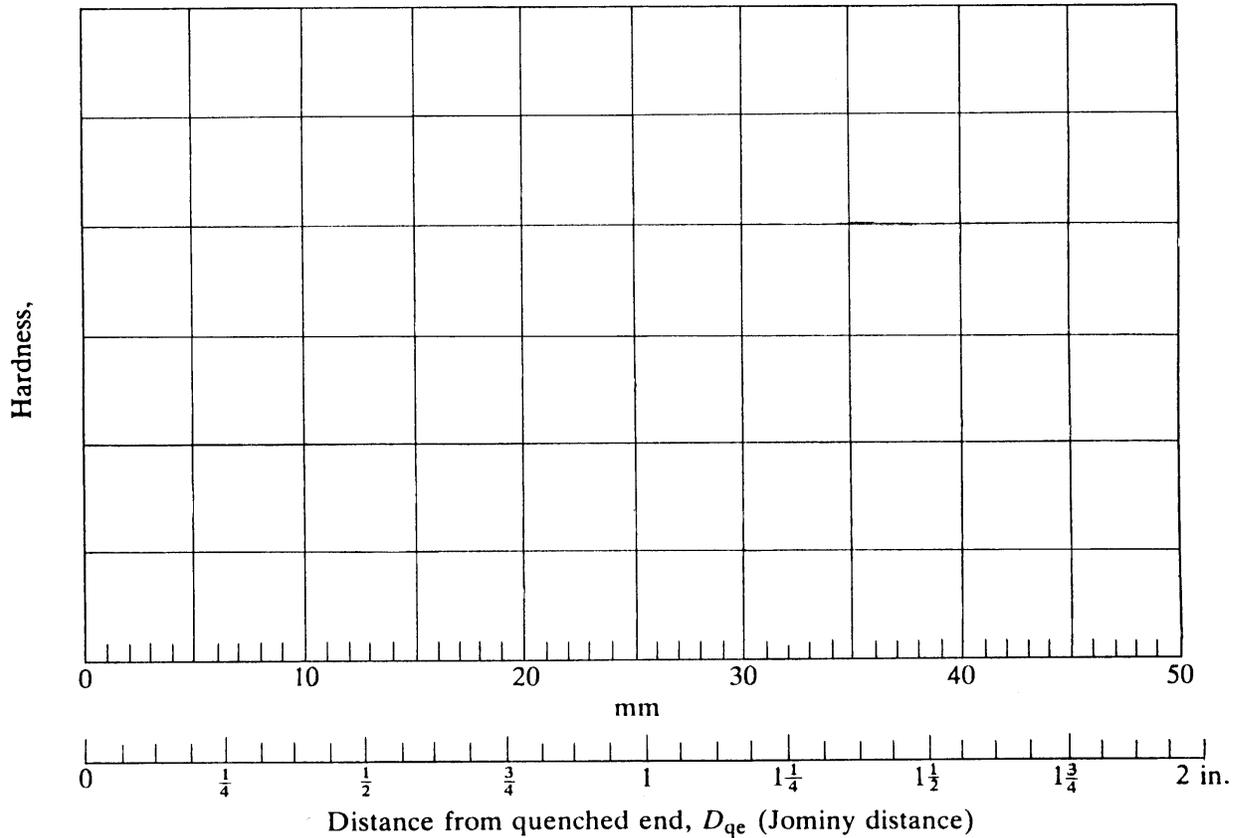
Date: _____

Name: _____

I. Material: **A** _____ **B** _____ **C** _____

Jominy Distance D_{qe} , in. (mm)	Hardness ()			Jominy Distance D_{qe} , in. (mm)	Hardness ()		
	A	B	C		A	B	C
0 (0)				10/16 (15.8)			
1/16 (1.6)				12/16 (18.9)			
2/16 (3.2)				1 (25.2)			
3/16 (4.7)				1 ¼ (31.5)			
4/16 (6.3)				1 ½ (37.8)			
6/16 (9.5)				1 ¾ (44.1)			
½ (12.6)				2 (50.4)			

II. Hardenability Curves



III. Using the experimental result, determine and compare the hardness profiles across the diameter of a _____ steel rod from oil quench and water quench on the same graph. The diameter of the rod is _____ *in*.

Precipitation Hardening of Aluminum Alloys

Objectives:

1. Observe the effects of nonequilibrium composition on the hardness of alloys.
2. Observe the effects of aging time on the hardness of nonequilibrium alloys.
3. Observe the phenomena of natural aging, artificial aging, and overaging.

Background:

The strength and hardness of some metal alloys may be enhanced by the formation of extremely small and uniformly dispersed particles of a different phase within the original phase matrix. This can be accomplished with appropriate heat treatments. A process that can accomplish this is called *precipitation hardening* because the minute particles are termed "precipitates." *Age hardening* is also used to describe the process because the strength and hardness develop with time, or as the alloy ages. Examples of alloys that can be hardened by precipitation treatment include Al-Cu, Al-Si, Cu-Be, Cu-Sn, and Mg-Al. Some ferrous alloys are also precipitation hardenable.

Precipitation hardening requires that the solute in the two-phase solid has a decreasing solubility with decreasing temperature. The section of Al-Cu phase diagram (Figure 1) indicates this condition for a Cu content of less than 5.65%. The solubility of copper in aluminum decreases to almost nonexistent as the temperature decreases.

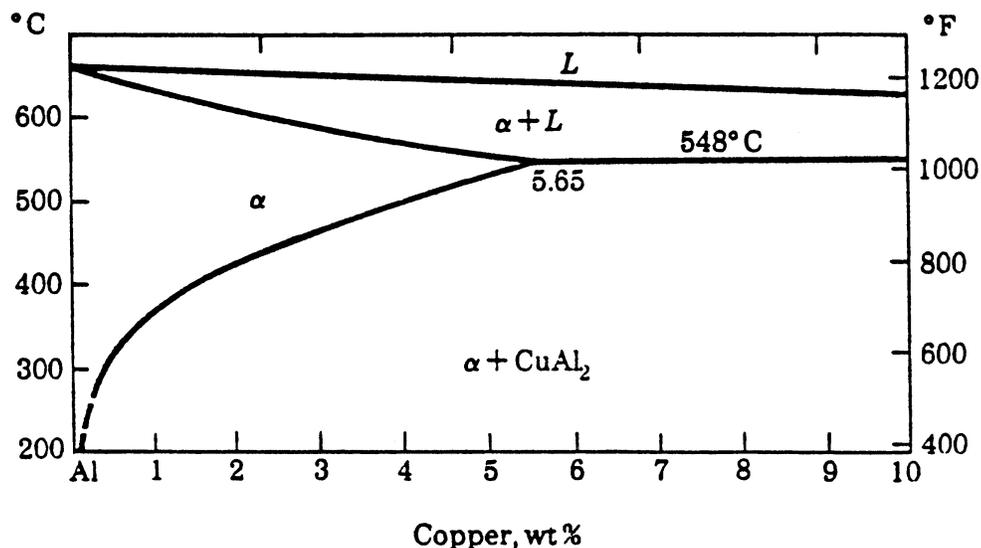


Figure 1 - Phase diagram of aluminum-copper with copper content up to 10%.

The precipitation hardening of Al-Cu alloys is a three-step process. The process for an Al-Cu alloy containing less than 5.65%Cu involves (1) a solution heat treatment at about 540°C (1000°F) in which the θ phase (CuAl₂) at grain boundaries is dissolved and

the copper atoms redistributed uniformly in the α matrix, forming a homogeneous solid solution, (2) a rapid cooling (quench) of the alloy to room temperature to avoid equilibrium formation of θ phase, and (3) a natural aging at room temperature or artificial aging at an elevated temperature. In the rapid cooling step, the cooling occurs so quickly that formation of equilibrium θ at grain boundaries cannot occur and a supersaturated solid solution remains at room temperature. In the aging step the supersaturated solid solution forms minute θ particles throughout the α matrix. The θ particles in the α matrix that are capable of interfering with dislocation movement, resulting in increases strength and hardness. If the alloy is heated for extended periods or at too high a temperature, the precipitates coarsens and the hardening effect diminishes. This is termed *over-aging*.

The properties of precipitation hardened alloys are greatly affected by the solution-heat-treatment temperature. If the heat treating temperature is too low, the θ phase at grain boundaries is not completely dissolved prior to quench and, therefore, the density of θ precipitates is low resulting in lower strength and hardness. If the heat treating temperature is too high, melting of some phases with low melting temperature can occur, resulting in a decrease in strength. For Al-Cu-Mg alloys, the normal commercial heat treatment practice is to solution-heat-treat about 5°C lower than the lowest melting eutectic.

Procedure:

An aluminum alloy containing approximately 5%Cu will be annealed, quenched, and aged to observed the effects of nonequilibrium composition, aging time, and overaging.

No.	Specimen Preparation	Observation
1	Anneal at 540°C (1000°F), furnace cool to achieve equilibrium composition	Rockwell B hardness
2	Anneal at 540°C (1000°F), remove from furnace and water quench, age at room temperature	Rockwell B hardness every 15 minutes
3	Anneal at 540°C (1000°F), remove from furnace and water quench, age at 225°C (437°F) for 5 minutes, water quench	Rockwell B hardness
4	Same as #3 but age for 10 minutes	Rockwell B hardness
5	Same as #3 but age for 15 minutes	Rockwell B hardness
6	Same as #3 but age for 20 minutes	Rockwell B hardness

7	Same as #3 but age for 30 minutes	Rockwell B hardness
8	Same as #3 but age for 40 minutes	Rockwell B hardness
9	Same as #3 but age for 50 minutes	Rockwell B hardness

Assignments:

1. Quench harden enough samples according to the datasheet. Measure hardness of each sample after the age hardening. During quench, stir the sample in water bath vigorously to break the steam pocket around the sample for efficient heat transfer. Dry the sample with a paper towel before placing it in the furnace for artificial aging.
2. Prepare a hardness vs. aging time graph showing the following two curves:
 - (a) natural aging of specimen #2.
 - (b) artificial aging of specimen #2 (0 aging time) to #9. Consider specimen #2 at time = 0 have been artificially aged at 225°C (437°F) for zero time.
3. Describe the differences between natural aging and artificial aging that you have observed.

MECH 210 – Materials Science and Engineering Laboratory
Precipitation Hardening of Aluminum Alloys

Date: _____

Name: _____

Material: _____

I. Heat Treatment Data

No.	Heat Treatment	Hardness (HRB)	Average Hardness (HRB)
1	<i>Heat treated at 545°C (1013°F) for _____ hrs, furnace cooled</i>		
<i>Natural aging at _____°C (_____°F)</i>			
2	for 0 minutes		
	for 10 minutes		
	for 20 minutes		
	for 30 minutes		
	for 40 minutes		
	for 50 minutes		
	for 60 minutes		
<i>Artificial aging at _____°C (_____°F)</i>			
3	for 5 minutes		
4	for 10 minutes		
5	for 15 minutes		
6	for 20 minutes		
7	for 35 minutes		
8	for 50 minutes		
9	for 65 minutes		

Glass-Transition Temperature Determination

Objectives:

1. Study the glass transition temperature of polymers.
2. Understand the principles for differential thermal analysis of phase transformations.
3. Use a differential scanning calorimeter to determine the glass transition temperature of a polymer material.

Background:

The glass transition temperature (T_g) is one of the most important properties of amorphous (noncrystalline) polymers. Above T_g , noncrystalline thermoplastics exhibit predominantly viscous behavior. Below T_g , polymers show glass-brittle behavior, thus the term *glass transition temperature*. In some ways T_g may be considered as a ductile-brittle transition temperature. In manufacturing processes, polymer can easily be formed into a desired shape at temperatures above its T_g and cooled below T_g to retain the shape.

The property transition of polymers at T_g actually is a gradual process over a temperature range. The transition is accompanied by the changes in heat capacity and thermal expansion coefficient as a polymer goes through its T_g . The glass transition temperature is conveniently taken as the temperature when the change in heat capacity is half completed. Therefore, the glass transition temperature can be accurately determined by careful measurements of the changes in heat capacity over the temperature range of transition.

The differential scanning calorimeter is a sensitive instrument capable of detecting a very small amount of energy change in a specimen. A typical differential scanning calorimeter has two small identical cells, one for test specimen and the other used as a standard. The standard cell usually does not contain specimen. The heating and cooling of the two cells are controlled by a computer with programmed starting temperature, heating rate, temperature range, cooling rate, and sensitivity.

On heating, the calorimeter measures differences in power input between the two cells for a preprogrammed constant heating rate. When the specimen undergoes an endothermic transformation (energy input required), more electrical power than that for the empty standard cell is needed for the specimen cell to maintain the same heating rate. On the other hand, less power will be needed for the specimen cell when the specimen goes through an exothermic transformation (energy is released). The computer (with a printer) records the power differential (ordinate axis on printer) as a function of elapsed time (abscissa axis on printer). Figure 1 shows a sample output from a differential scanning calorimeter. In general, the change in slope of the recorded curve indicates a transformation in the material. The temperature and amounts of energy involved in the transformation can then be extracted from the recorded results.

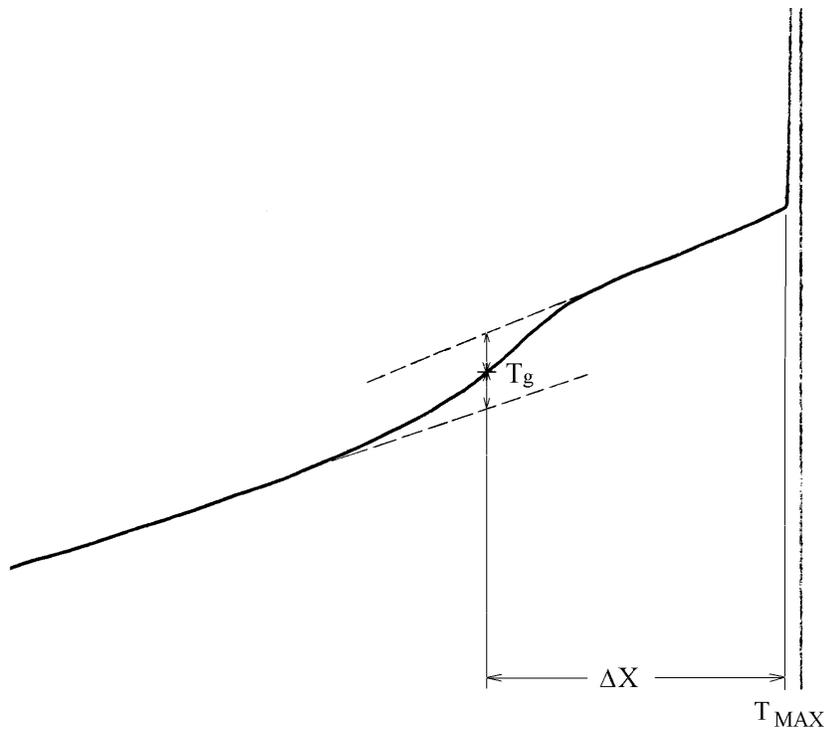


Figure 1 – A sample DSC output with T_g determined using Equation (1) and method illustrated in Figure 2.

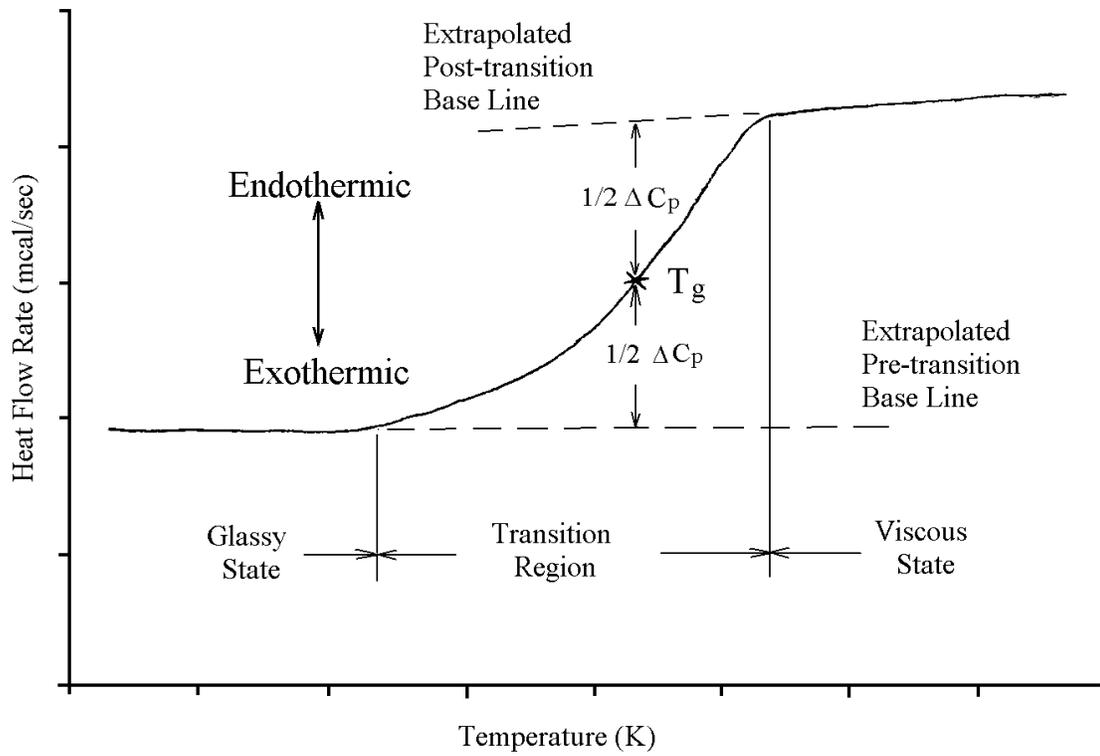


Figure 2 – Method for determination of glass transition temperature, T_g .

A polymer material goes through the transition between glassy state and viscous state over a transition temperature range. The temperature at which the transition is half finished is taken as the glass transition temperature, T_g . Two extrapolated base lines are drawn from the pre-transition and post-transition curves. The point on curve that bisects the vertical distance between the two base lines is where T_g will be calculated using Equation (1).

$$T_g = (T \text{ MAX}) - \left(\frac{\Delta X}{\text{PaperSpeed}} \right) (\text{HEAT RATE}) \quad (1)$$

where ΔX is horizontal distance measured between T_g and $T \text{ MAX}$ as shown in Figure 1.



Figure 3 – A Cole-Palmer differential scanning calorimeter used in this experiment.

It was observed by Williams, Landel, and Ferry that viscosity of a polymeric material is a function of polymer temperature and, therefore, is related to glass transition temperature of the polymer. They developed an equation, known as Williams-Landel-Ferry equation, that states:

$$\eta = \eta_0 \exp \frac{-17.4(T - T_g)}{51.6 + (T - T_g)} \quad (2)$$

where $\eta_0 = 10^{12} \text{ Pa}\cdot\text{s}$, and T and T_g are polymer temperature and glass transition temperature, respectively, in K .

Procedure:

The experiment involves preparing the specimen, setting up the controller, conditioning the specimen, and running the test. Several tests will be conducted to obtain an average glass transition temperature.

Specimen Preparation:

1. Obtain a polymer specimen, two small aluminum pans, and two aluminum pan covers.
2. Place the polymer specimen in one of the aluminum pans, and a cover over the specimen. The pan and cover are then crimped together over the polymer specimen.
3. Remove the draft shield on the calorimeter and open the sample holder enclosure by pushing the latch upwards and swinging the enclosure cover counterclockwise 180°.
4. Using tweezers, remove the platinum pan covers in the two cells.
5. Place the aluminum pan with sample inside in the left-hand sample cell and the other empty aluminum pan with cover in the right-hand cell.
6. Using tweezers, replace the platinum pan covers.
7. Close the enclosure cover by swinging it clockwise and pressing down the lever.
8. Replace the draft shield.

Printer Setup:

1. Set paper speed at 5 cm/min.
2. Turn the **ZERO** knob to bring the pen to the right-hand edge of paper.

Controller Setup:

All keys need to be depressed for at least 0.5 seconds.

1. Push the **POWER** switch on the DSC-4 to **ON** position.
2. Push the **POWER** switch on the DSC-4 microprocessor controller to **ON** position.
3. Press the **MANUAL MODE** key and the **RESET** key simultaneously to enter the manual mode of operation.
4. Press the command key **SET UP** to start a step-by-step setup routine. The setup routine lights up the parameter keys one at a time. As each parameter key is lighted the operator can enter a numerical value for that parameter and press **ENTER** to enter.
5. Enter the following parameters:

T MIN	= 25°C
T MAX	= 160°C
HEAT RATE	= 25°C/min

COOL RATE = 0 (for rapid cooling)

T SPAN = 400°C (default)

6. Set the plotting range to 10 *mcal/sec* on the differential scanning calorimeter (DSC-4).
7. Press the **HEAT** key to initiate the temperature program. The calorimeter will take the specimen temperature from the minimum temperature to maximum temperature at the specified heating rate.
8. Push the power switch on the printer to **ON** and lower the pen for plotting.
9. When the maximum temperature is reached, push the power switch on the printer to **OFF** and raise the pen.
10. Wait until the sample temperature returns to a constant minimum temperature before the next run.

Shut Down:

1. Push the power switches on the DSC-4, controller, and printer to **OFF**.
2. Remove the sample from the sample cell and replace the draft shield.

Assignments:

1. Obtain a sample from the instructor.
2. Generate a curve using the differential scanning calorimeter for the sample using parameters specified by the instructor.
3. Determine the glass transition temperature for the sample and record it on the datasheet.
4. Answer the questions on the datasheet.

MECH 210 - Materials Science and Engineering Laboratory
Glass Transition Temperature of a Polymer

Date: _____

Name: _____

1. Determine the glass transition temperature for the sample material using the following data reduction method based on the differential scanning calorimeter output.

$$T_g = (T_{MAX}) - \left[\left(\frac{\Delta X}{\text{Paper Speed}} \right) \right] (\text{HEAT RATE})$$

Experiment Data

	Run #1	Run #2	Run #3	Run #4	Run #5	Run #6
T MAX (°C)						
HEAT RATE (°C)						
ΔX (cm)						
Paper Speed (cm/min)						
T _g (°C)						
Material:	Average T _g (°C):					

2. Is the transition on heating an exothermic or endothermic reaction? Explain.

3. Do you see anything special as suggested by Equation (2)?

4. (a) Estimate the viscosity of this polymeric material at 200°C.

(b) What is the viscosity of this polymeric material at its T_g?

Infrared Spectroscopy of Polymers

Objectives:

1. Learn the theory of infrared (IR) spectroscopy.
2. Prepare IR spectroscopy samples and collect IR spectra.
3. Use infrared spectroscopy to identify polymers.

Background:

Infrared spectroscopy is a type of spectroscopy that uses the infrared portion (wavelength from 2.5 to ~15 μm or wavenumber from 4000 to 600 cm^{-1}) of the electromagnetic spectrum. As with all spectroscopic techniques, it can be used to investigate the composition of a sample.

Infrared spectroscopy works because chemical bonds have specific frequencies at which they excite. The specific frequency, called resonant frequency, is dependent on the length of the bond and the mass of atoms at either end of it. Thus, the frequency causing the excitation can be correlated to a particular chemical bond type.

In measuring a sample, a beam of monochromatic infrared light at a specific frequency is passed through the sample. If the infrared light frequency is the same as the resonant frequency of a type of chemical bond in the sample, the chemical bond excites and the infrared radiation is absorbed by the sample resulting in a low transmission. By repeating this operation across a range of frequency, a chart relating percent transmission and infrared light frequency (in terms of wavenumber), called spectrum, can be built up. An example of infrared spectrum for low-density polyethylene is shown in Figure (1).

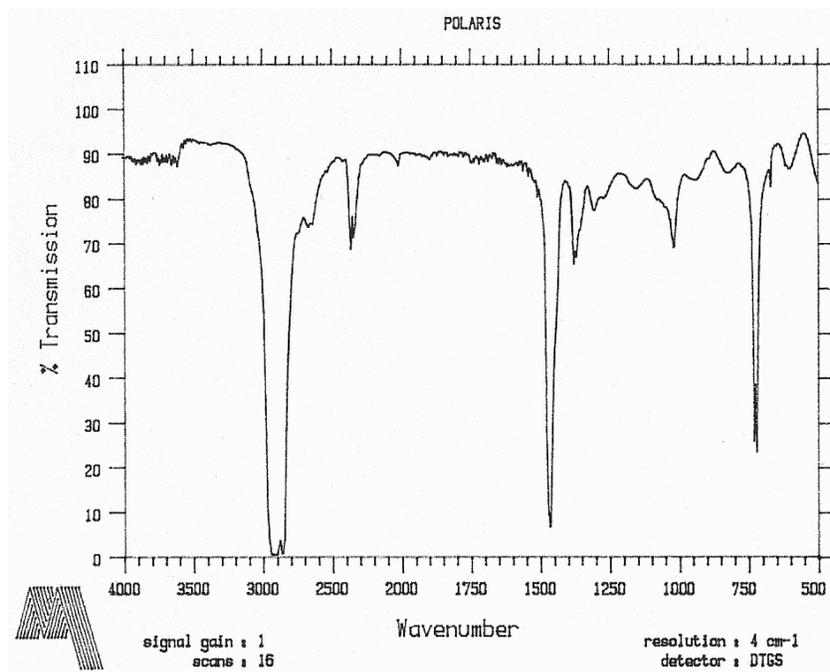


Figure 1 – An infrared spectrum for low-density polyethylene (LDPE).

The wavenumber in an infrared spectrum is related to the wavelength, and thus frequency, of the infrared radiation by the following equations.

$$\text{Wavenumber} = \frac{1}{\text{Wavelength}} = \frac{1}{\lambda} \quad (1)$$

$$\text{Velocity of light } (C) = \frac{\text{Frequency}(\nu)}{\text{Wavelength}(\lambda)} \quad (2)$$

The unit for wavenumber is cm^{-1} in Equation (1), therefore wavelength should be converted to centimeters (cm) rather than meters (m). The parameters in Equation (2) are velocity of light (C) in m/s , frequency (ν) in Hz , and wavelength (λ) in m .

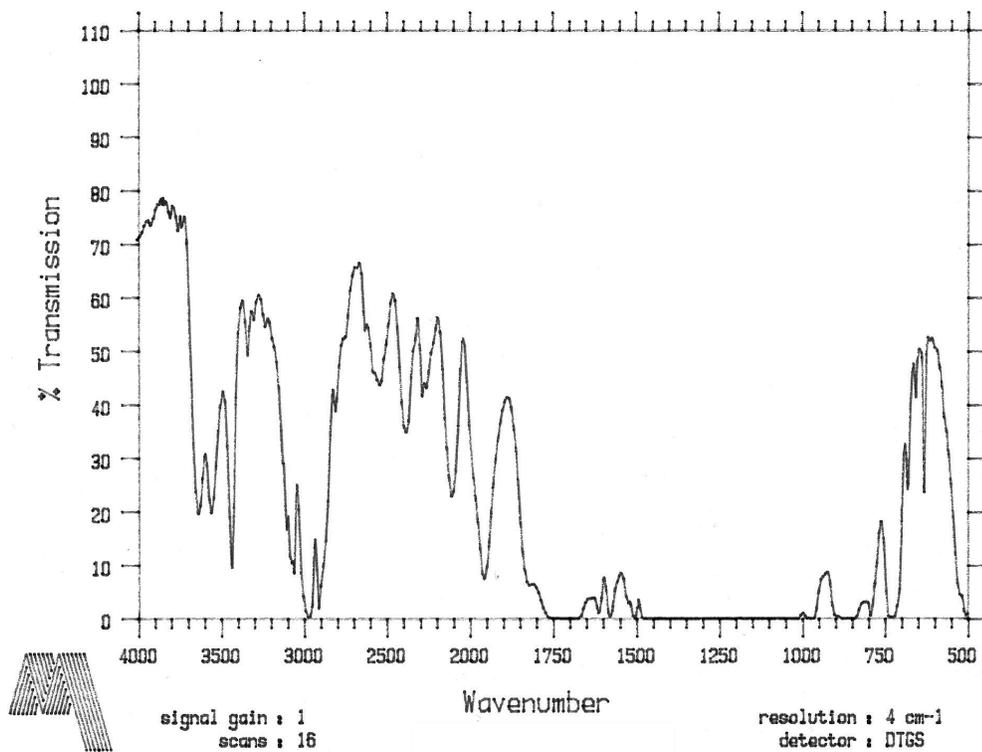
The major peaks of low transmission (of infrared radiation through samples) on the infrared spectra, such as those in Figure 1, are almost exclusively associated with covalent bonds. Clear spectra can be produced by samples with high levels of purity. There are six ways of vibration excitation of chemical bonds that can cause low transmission: asymmetric stretching, symmetric stretching, scissoring, rocking, wagging and twisting. However, chemical bonds can also rotate and bend as a result of the absorption of infrared radiation. Each type of bond excitation can occur at somewhat different frequencies. Still, the presence of major peaks at associated wavenumbers can be used to identify the chemical composition of a substance.

For routine investigation of chemical composition or molecular structure, the absorption of infrared radiation due to stretching vibration is probably the most important one to consider. The regions of infrared radiation absorption observed in common organic molecules are those listed Table 1.

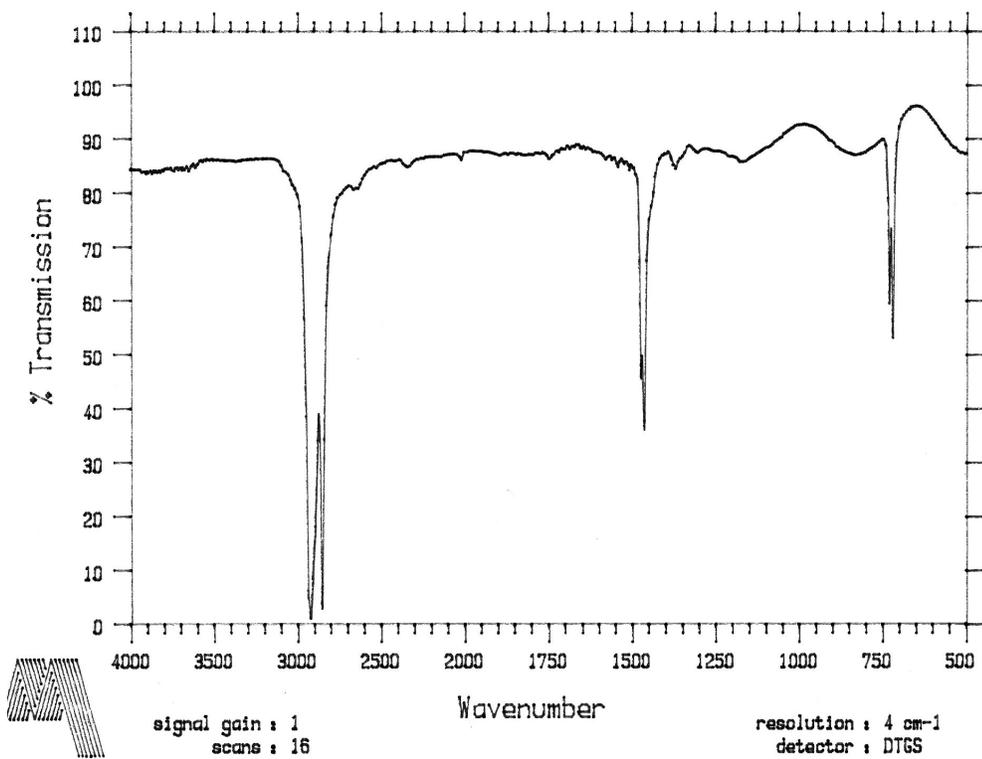
Table 1 – Typical regions of infrared radiation absorption for stretching vibration of chemical bonds in organic molecules.

Wavenumber (cm^{-1})	Stretching Vibration of Bond Types
3700 - 2500	X-H with X = C, N, O, S
2300 - 2000	$\text{C}\equiv\text{X}$ with X = C or N
1900 - 1500	$\text{C}=\text{X}$ with X = C, N, O
1300 - 800	C-X with X = C, N, O

Most organic molecules have single bonds and they undergo different types of excitation in different environments. It is not surprising the region below wavenumber of 1500 cm^{-1} usually contains many peaks of low transmission and becomes quite complex. The peaks in this region often are difficult to assign to bond types. This region is referred to as the “fingerprint region” because the absorption pattern in this region is uniquely characteristic of a given compound. The identity of a compound can be confirmed by comparison of this region to a known spectrum. With thousands of spectra of known substances stored in a database, a sample can be quickly identified through computerized comparison. Additional infrared spectra of some common polymers are shown in Figures 2 and 3.

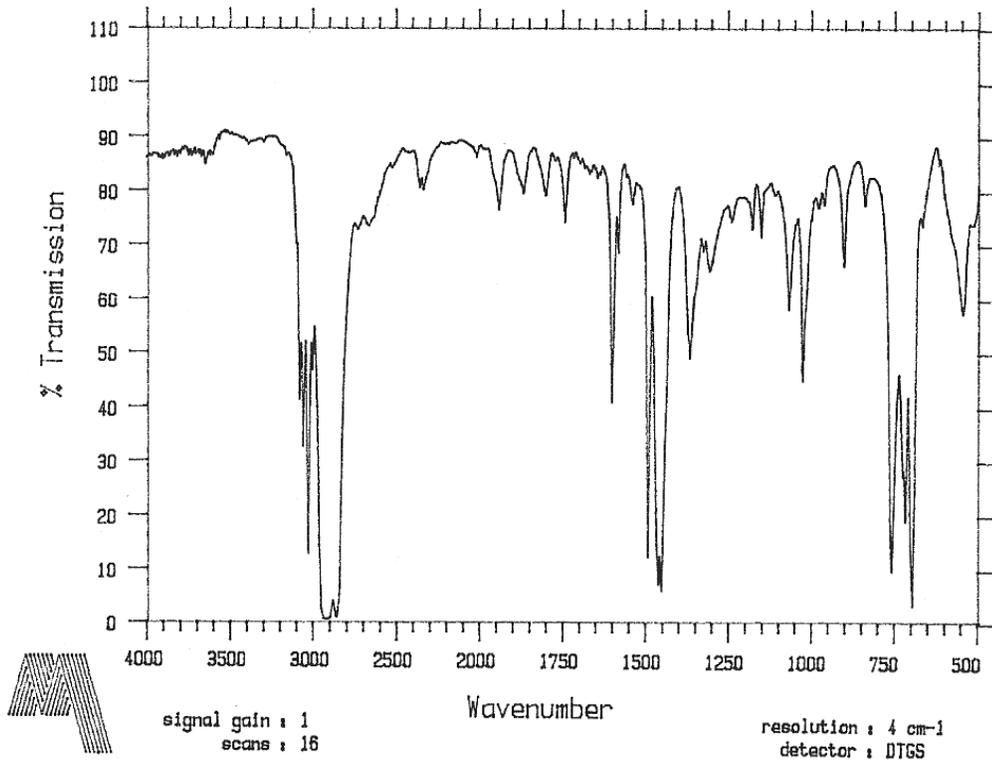


(a) Polyethylene terephthalate (PETE)

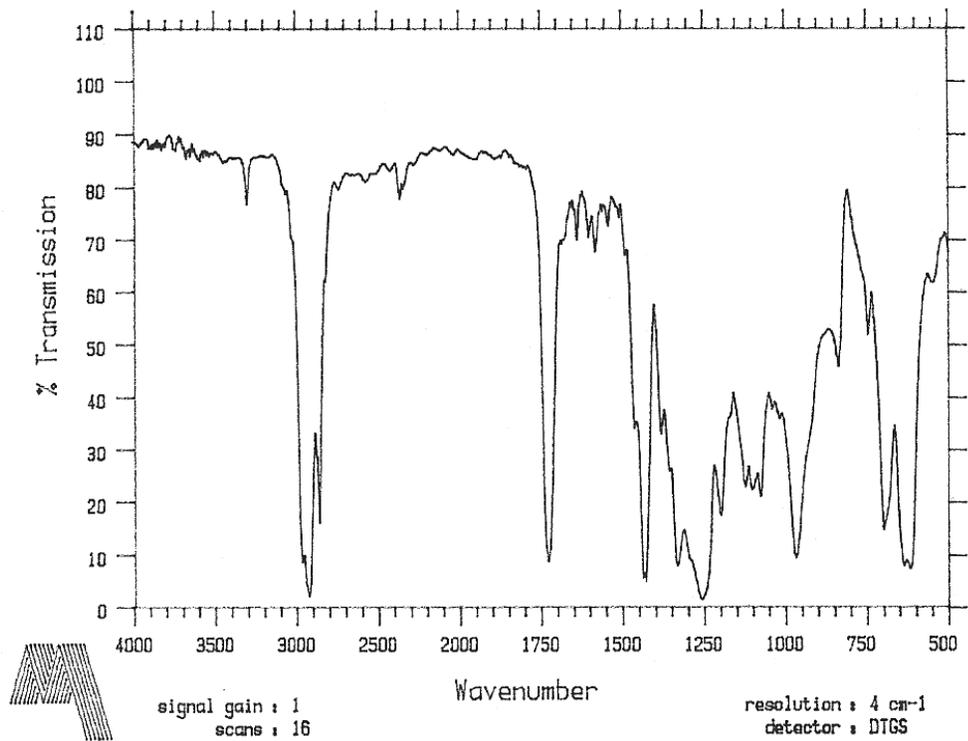


(b) High-density polyethylene (HDPE)

Figure 2 – Infrared spectra of (a) polyethylene terephthalate and (b) high-density polyethylene.



(a) Polystyrene (PS)



(b) Polyvinyl chloride (PVC)

Figure 3 – Infrared spectra of (a) polystyrene and (b) polyvinyl chloride.

Operating Procedure for the Mattson FT-IR Spectrometer

Start-up procedure

1. Turn on cold cooling water in the sink to the right of the spectrometer to a medium-high flow.
2. Turn on power strip placed behind left side of the spectrometer.
3. Turn on the HP plotter on top of the spectrometer if it is not already on. Insert a sheet of paper in the plotter.
4. Wait 30 seconds for the spectrometer to initialize.
5. Push the two vertical closure levers (in front of the HP plotter on top of spectrometer) down.
6. Press the blue "Setup Menu" button twice, then press the blue "Next Menu" button once to initialize IR with current settings.
7. Pull up the closure levers, open sample compartment by twisting the four locking knobs in counterclockwise direction and lifting.
8. Remove any samples from the sample chamber, replace cover, lock the cover by twisting the knobs in clockwise direction, push the closure levers down, and press the green "Collect Background" button. Wait until the background collection is completed.
9. Pull up the closure levers, open sample compartment, insert a sample, close the sample compartment, and push the closure levers down.
10. Turn on plotter and press the green "Collect Sample" button. The spectrum will automatically plot on the HP plotter when collection of sample spectrum is finished.
11. Repeat steps 8-9 for a new sample.

Shut-down procedure

1. Turn off power strip behind the spectrometer.
2. Turn off cooling water to the right of spectrometer.
3. Clean up your samples.

Assignments:

1. Select a sample from those offered by the instructor. Record the sample number and the source of the sample. If the source of the sample is not clear, ask the instructor.
2. Cut a small piece of sample, about 1" × 1" in size, and mount it on the sample holder with masking tape. Make sure the sample is fully exposed within the window area. Write the sample number on the sample holder.
3. Follow the operating procedure of the IR spectrometer to collect an infrared spectrum.
4. Compare the collected spectrum with example spectra and identify the sample material.
5. Complete this assignment/data sheet and turn it in with the spectrum. Write the sample number and material type on the spectrum.

MECH 210 – Materials Science and Engineering Laboratory
Infrared Spectroscopy of Polymers

Date : _____

Name: _____

Lab Section: _____

Data from Infrared Spectroscopy Experiment

Sample No.: _____

Sample Thickness: _____ mm

Description and Source of Sample:

1. Sample material based on infrared spectrum*: _____
(* Attach the collected sample spectrum to this report sheet.)

2. Show the mer structure of the material.

3. Which peak on the attached infrared spectrum is from stretching vibration of the C-H bonds in the sample material?

MECH 210 – Materials Science and Engineering Laboratory

Excel Spreadsheet Graphing Exercise

The following exercise demonstrates useful techniques for plotting tensile test data using Microsoft Excel.

Plot the given data from the tensile test of a stainless steel. The original diameter is 0.505 in. and the initial gauge length is 2.000 in.

Length (in.)	Load (lb _f)
2.000	0
2.001	2850
2.002	5710
2.003	8560
2.004	11400
2.006	17100
2.008	20000
2.010	20800
2.015	23000
2.020	24200
2.030	26800
2.040	28800
2.080	33650
2.120	35750
2.140	36000
2.160	35850
2.200	34050
2.230	28000

Procedure:

Enter data and formulas for calculation

1. Bring up the Excel spreadsheet by clicking **Start, Programs, and Microsoft Excel**. Adjust the size of the Excel window by clicking, holding down the left mouse button, and dragging the boundaries.
2. Click and drag from cell A1 to D1 to highlight the cells.
3. Click **Format, Column, Width** and change the column width to **10**. Click **OK** to activate the change and return to the spreadsheet.
4. Type **Length (in)** in cell A1 and **Load (lb)** in cell B1
5. Enter data in columns A and B with values for length in cells A2 to A19, values for load in cells B2 to B19.

6. Type **Strain (in/in)** in cell C1 and **Stress (psi)** in cell D1
7. Type $=\text{(A2-2.000)}/\text{2.000}$ in cell C2 and press **Enter** to calculate the strain. The Excel recognizes that you are entering an equation when you type the “=” sign. The strain value appears in the cell when you hit the **Enter** button.
8. Click to highlight and select cell C2.
9. Click **Edit** on the Tool Bar and select **Copy** on the pull-down menu.
10. Click and drag to highlight cells C3 to C19. Click **Edit** on the Tool Bar and select **Paste** on the pull-down menu. The equation will be copied into these cells and strain values calculated.
11. Type $=\text{B2}/\text{(3.14*0.505*0.505/4)}$ in cell D2 and press **Enter** to calculate the stress corresponding to the load shown in cell B2. The calculated stress should appear in the cell once you hit the Enter button.
12. Click to highlight and select cell D2.
13. Click **Edit** on the Tool Bar and select **Copy** on the pull-down menu..
14. Click and drag to highlight cells D3 to D19. Click **Edit** on the Tool Bar and select **Paste** on the pull-down menu. The equation will be copied into these cells and the corresponding stresses calculated.
15. Click and drag to highlight cell range C2 to D19. Click **Format, Cells, Number** and change the number of decimal places to **4**. Click OK to return to the spreadsheet.

Plot Data

16. Click and drag to highlight cell range C2 to D19.
17. Click the **ChartWizard** icon to create a chart (graph) using the data just selected.
18. *Step 1 of 4* window (Chart Type) appears. Select the chart type **XY(Scatter)** and the chart sub-type that shows only the data points without any curves.
Click **Next**.
19. *Step 2 of 4* window (Chart data Source) appears. The data range and plot are shown.
Click **Next** if the graph is what you desire.
20. *Step 3 of 4* window (Chart Options) appears.
Enter **Figure 1 - A Stress-strain curve for stainless steel** for chart title.
Enter **Strain, in/in** for Values (X) Axis.
21. Enter **Stress, psi** for values (Y) Axis.
22. Click **Next**.
23. *Step 4 of 4* window (Chart Location) appears. Select **As new sheet** and click **Finish**.
24. Click the legend (Series 1) located outside the graph and drag it inside the graph. The graph size can be adjusted by clicking and dragging the boundaries of the graphing area.

25. Click to select the legend and type the legend information **Stainless Steel** and press **Enter**. The legend appears in the graph, its location can be changed by clicking and dragging the frame of the legend.
26. Click the "Series 1" legend and press **Delete** key to hide the unnecessary legend.
27. The font, font style, and font size of the chart title and parameter names (X and Y axes) can be modified. To make changes, double click on them to bring up the Format window and enter new selections.
28. The background color can also be changed by double-clicking in vacant parts of the plot (away from data points) and make a new selection in the Format Plot Area Window.

Add Trendline (Curve) and Equation:

29. Click one of the data points to identify the data group. All the data points in the same group will be highlighted.
30. From the **Chart** menu, select **Add Trendline** and the type of trendline and order (of polynomial equation if chosen), click the **Options** tab and select **Display equation on chart**, and click **OK** to insert the trendline and equation.
31. Click and drag the equation to a more appropriate location, if desired.

Note: The trendline may not be always a best-fit curve through all the data points. Another approach (recommended for reports in this class) is to plot only the data points and enter the best-fit curve manually using curve board.

Organization: _____ /

Experiment Data: _____ /

Calculation: _____ /

Discussion: _____ /

TOTAL: _____ /

Stress Concentration Experiment

MECH 210 – 02 Materials Science and Engineering

John Smith

September 21, 2005