1   Objective

To use the Rockwell and Brinell tests to create deformations and compare results of various metals and alloys. These tests will help better understand how mechanical stress and strain behave.

# 2   Experimental Procedures

2.1   Rockwell hardness test

We placed a piece of metal into the machine and turned the crank shaft near the bottom of the machine until the piece locked into place and the small arrow on the dial was pointing towards the black dot. At this point there is a minor load of 10 kg being applied to the material. We then twisted the dial adjustment shaft directly under the crank shaft to zero the machine. Zeroing the machine meant aligning the long arrow with the black 0 mark on the dial. Then we pushed down on the handle to apply the 60 kg major load and started a 15 second timer. After the 15 seconds we pulled forward on the handle located on the bottom right side of the machine to release the load. We measured the results using the black – not red – tick marks on the dial and then twisted the crank shaft to release the material.

2.2   Brinell hardness test

We placed the piece in the machine and used a similar crank shaft to lock the piece into place. Then we turned the pressure knob near the top of the machine until it was just tight enough where it would not come loose by itself. Then we began pulling the lever and pumping the pressure up to the required position (500 kg or 3000 kg) and starting our time for the required time (30 seconds or 15 seconds). We knew to start the timer right when the ball supporting the weights on the machine lifted up and started floating.

Figure 1: schematic of rubber plate used
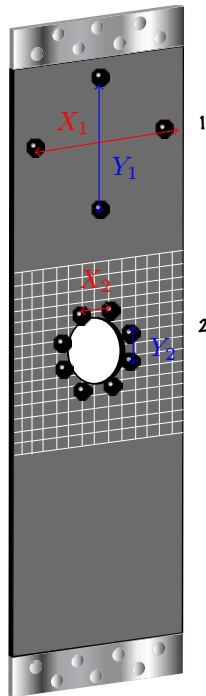
2.3   Stress Concentration Analysis

Refer to Figure 1 for reference. We initially measured the width and depth of the rubber plate at the top of the plate and at the bottom near the hole. Then we measured $x_1\,y_1\,x_2\,y_2$. We then consecutively added 10 lbs to the load of the rubber sheet and remeasured $x_1\,y_1\,x_2\,y_2$ again after every 10 lbs.

3   Experimental Results

Material	Trial #	Major load (kg)	Minor load (kg)	Scale (0.002 mm)	Hardness	Conversion to Brinell
Mild Steel	1	60	10	Rockwell A	52.6	167
	2	60	10	Rockwell A	52.0	164
	3	60	10	Rockwell A	52.0	164
	average	60	10	Rockwell A	52.2	164
Stainless Steel	1	60	10	Rockwell A	55.9	191
	2	60	10	Rockwell A	53.5	173
	3	60	10	Rockwell A	54.5	179
	average	60	10	Rockwell A	54.6	180
Brass	1	60	10	Rockwell A	37.0	88
	2	60	10	Rockwell A	37.5	90
	3	60	10	Rockwell A	37.9	91
	average	60	10	Rockwell A	37.5	90
Aluminum	1	60	10	Rockwell A	38.9	94
	2	60	10	Rockwell A	39.0	94
	3	60	10	Rockwell A	38.0	91
	average	60	10	Rockwell A	38.6	92
Copper 0.250	1	60	10	Rockwell A	27.0	68
	2	60	10	Rockwell A	25.8	66
	3	60	10	Rockwell A	29.1	72
	average	60	10	Rockwell A	27.3	69
Copper 0.230	1	60	10	Rockwell A	32.0	−
	2	60	10	Rockwell A	31.1	−
	3	60	10	Rockwell A	30.6	−
	average	60	10	Rockwell A	31.2	−
Copper 0.156	1	60	10	Rockwell A	31.9	−
	2	60	10	Rockwell A	32.6	−
	3	60	10	Rockwell A	34.2	−
	average	60	10	Rockwell A	32.9	−
Copper 0.066	1	60	10	Rockwell A	39.9	−
	2	60	10	Rockwell A	39.9	−
	3	60	10	Rockwell A	39.5	−
	average	60	10	Rockwell A	39.8	−

Figure 2: Rockwell test results for all metallics

Material	Trial #	Load P (kg)	Indentation diameter d (mm)	Load ÷ Projected Area (kg/mm^2)	Load ÷ Indentation Area (kg/mm)
Mild Steel	1	3000	4.4	2.0×10^2	1.9×10^2
	2	3000	4.5	1.9×10^2	1.8×10^2
	average	3000	4.45	1.93×10^2	1.8×10^2
Stainless Steel	1	3000	4.4	2.0×10^2	1.9×10^2
	2	3000	4.6	1.8×10^2	1.7×10^2
	average	3000	4.5	1.9×10^2	1.8×10^2
Brass	1	500	2.6	94	93
	2	500	2.7	87	86
	average	500	2.65	90.7	89
Aluminum	1	500	2.5	1.0×10^2	1.0×10^2
	2	500	2.6	94	93
	average	500	2.55	97.9	96
Copper 0.250	1	500	2.7	87	86
	2	500	2.9	76	74
	average	500	2.8	81	80

Figure 3: Brinell test results for metallics

Projected area $A_p = \pi(\frac{d}{2})^2$ where d is the indentation diameter

Indentation Area $A_i = \frac{\pi D}{2}(D - \sqrt{D^2 - d^2})$ where D is the diameter of the penetrator ball (mm)

Load P (lb)	x_1 (in)	x_2 (in)	y_1 (in)	y_2 (in)	Nominal stress (psi)	Local stress (psi)	Nominal x_1 strain (in/in)	Local x_2 strain (in/in)	Nominal y_1 strain (in/in)	Local y_2 strain (in/in)
0	$4\frac{58}{64}$	$\frac{32}{64}$	$4\frac{63}{64}$	$\frac{32}{64}$	0	0	-	-	-	-
10	$4\frac{56}{64}$	$\frac{32}{64}$	$5\frac{2}{64}$	$\frac{33}{64}$	0.408	38.8	-6.37×10^{-3}	0	9.40×10^{-3}	31.3×10^{-3}
20	$4\frac{55}{64}$	$\frac{31}{64}$	$5\frac{2}{64}$	$\frac{34}{64}$	0.818	77.6	-9.55×10^{-3}	-31.3×10^{-3}	9.40×10^{-3}	62.5×10^{-3}
30	$4\frac{53}{64}$	$\frac{31}{64}$	$5\frac{5}{64}$	$\frac{35}{64}$	1.23	116	-15.9×10^{-3}	-31.3×10^{-3}	18.8×10^{-3}	93.8×10^{-3}
50	$4\frac{53}{64}$	$\frac{31}{64}$	$5\frac{10}{64}$	$\frac{37}{64}$	2.04	194	-15.9×10^{-3}	-31.3×10^{-3}	34.5×10^{-3}	156×10^{-3}

Figure 4: Stress concentration measurements from rubber sheet

4 Discussion

1) Using conversion charts provided in the laboratory, converge average Rockwell A numbers to equivalent Brinell numbers. Can you suggest a reason for the poor agreement between converted and measured Brinell numbers in some cases?

Figure 5 below shows the percent difference between the measurements. An average percent difference of 5.90% was calculated. One reason for this high error is that the converted Rockwell A numbers are more prone to random errors as it is a two step process. First there is random error in the initial measurement of the Rockwell A numbers and then random error when converting to Brinell. There is also human error involved during the Brinell test. When using the microscopes to measure the diameter of the indentation, it is often difficult to decide where the edges of the circular indentation start; this causes some error in measurements.

Material	Rockwell A conversion to Brinell (average)	Brinell test	% difference
Mild Steel	164	180	9.30
Stainless Steel	180	180	0
Brass	90	89	1.12
Aluminum	92	96	4.26
Copper 0.250	69	80	14.8

Figure 5: Rockwell and Brinell comparation for question 1

2) What if the Brinell hardness number were defined by a much simpler function, namely, the load (P) divided by the projected area A_p of the impression, defined above? How does this number change with a change in applied load for the materials you tested in this lab? Would this quantity (P/A_p) be as good a hardness index as the BHN (= P/A_i)? Ex- plain.

If we make a small assumption as say that $D \approx d$ we can see that the projected area is in fact the indentation area. This assumption makes sense as the diameter of the indendation will most likely be very similar to the diameter of the sphere doing the indendation.

$$
\begin{aligned}
A_i &= (\frac{\pi}{2})^2 D \left(D - \sqrt{D^2 - d^2}\right) \\
&= (\frac{\pi}{2})^2 d \left(d - \sqrt{d^2 - d^2}\right) \\
&= (\frac{\pi}{2})^2 d^2 \\
&= A_p
\end{aligned}
\tag{1}
$$

Looking at figure 3 above, we can see the projected area hardness values are very similar to the indendation area values; this suggests that the assumption above does in fact make sense. Both the hardness values for using the indentation area and the projected area are very similar. This suggests that we can in fact just use the projected area when calculating Brinell hardness and still get a good value.

3) A hardness test can be used to give a rough estimate of a material's strength. A tensile test, in which a specimen is strained to complete failure, is obviously a much more accurate test of strength. Why would hardness tests ever be used instead of tensile tests? Give three reasons. Which test would you use in engineering design? Which test would you use for quality control? Explain.

One reason is that the hardness test is simpler and inexpensive. Tensile strengths require the material to fracture and break while the hardness test can be performed multiple times on the same material without having to toss it out and use a new sample. Another reason is that the tensile strength of a material can be calculated from that materials hardness using a simple conversion chart; this means that a hardness test can be used to calculate tensile strength. A third reason might be that the equipment needed is simpler and easier to use. A hardness test requires a steel or diamond ball to use as an indenter while a tensile machine would be much bigger and complex in order to pull a material apart.

I would still use an tensile test for engineering design to see when my material would fracture as this is quite important when building bridges, buildings, etc. You do not want anything to fracture. For quality control, a hardness test would be enough to test the quality of a material.

4) Using your data from the opaque rubber plate sample, plot longitudinal and transverse strain versus nominal applied stress (load divided by cross sectional area) for positions 1 and 2. Note that this amounts to a plot of gross section stress against the y_1 and x_1 strains as well as the net section stress against the y_2 and x_2 strains (4 plots total). Plot

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stress on the ordinate (y-axis) and the strain on the abscissa (x-axis). Remember that these are the applied stresses and may not be equal to the local stresses. What position in the opaque rubber plate sample that you tested is subjected to the highest tensile stress? Note that this will be the position of highest tensile strain for the same applied load. What position in the plate sample is subjected to the highest compressive stress? As above, this will be the position of highest compressive strain for the same applied stress.

The y_2 plot has the highest amount of strain on it – almost four times as much stress as any other point (x_1, x_2, y_1). Refer back to figure 1 to see where y_2 is positioned on the rubber sheet. The x_2 has the highest amount of compressive strain on it, but is quite close to the x_1 plot as well.
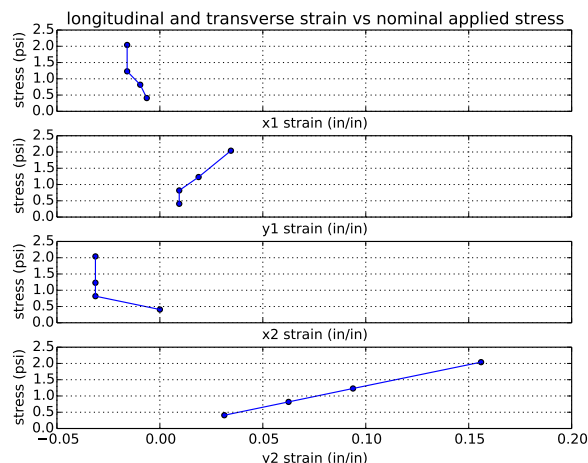

Figure 6: A plot of the longitudinal and transfverse strain vs nominal applied stress. All four subplots share the same axis values (x,y). There were four test points for each subplot; these represent 10, 20, 30, and 50 lb weights being used.

5) **What is the ratio between the highest tensile stress and the average longitudinal tensile stress, known as the "stress concentration factor?" Stress concentration can be easily obtained from your plots using a vertical line connecting two data sets for locations 1 and 2.**

Come back to this

6) **Using your data from the transparent photoelastic plate sample, rank the relative stress concentration at all four (4) non-circular openings from highest to lowest. Explain your results. Why should the shape of a "stress-raiser" matter?**

The holes with the smaller radi of curviture have the highest number of cycles and thus contain more stress in them. The holes with large radi of curviture (second sheet, bottom) have a smaller number of cycles and less stress. As a result, we must take into consideration the shape of holes/cracks that form in materials as the stress can vary greatly.

Rank	# cycles	location
1	$2\frac{2}{3}$	first sheet, top
1	$2\frac{2}{3}$	second sheet, top
3	$2\frac{1}{3}$	first sheet, bottom
4	$1\frac{2}{3}$	second sheet, bottom

Figure 7: ranking for transparent photoelastic sheets. Cycles represents the number of color changes, i.e. yellow $\rightarrow$ red $\rightarrow$ green is one complete cycle.

5

7) When a uniaxial stress σ_y is applied to a material (Fig. 8), there are resulting elastic strains (ϵ_y and ϵ_x) along both the y and x directions that are proportional to the applied stress, where E is Young's Modulus and υ is Poisson's Ratio. Write down the expressions for ϵ_y and ϵ_x when the same part is subject to a biaxial stress state, that is, both σ_x and σ_y, as illustrated in Fig. 9. Hint: the principle of "superposition" applies here. Begin by writing the equations for the strains when only σ_x is applied, add the equations for the strains when only σ_y is applied (above), and simplify.

$$\epsilon_x = \frac{\sigma_x}{E} \Rightarrow -\epsilon_y \upsilon = \frac{\sigma_x}{E} \Rightarrow \epsilon_y = \frac{-\sigma_x}{\upsilon E}$$

$$\epsilon_y = \frac{\sigma_y}{E}, \; \epsilon_x = \frac{-\upsilon\sigma_y}{E}, \; \epsilon_x = \frac{\sigma_x}{E}, \; \epsilon_y = \frac{-\sigma_x}{\upsilon E}$$

Add the two equations for both ϵ_x and ϵ_y.

$$2\epsilon_y = \frac{-\sigma_x}{\upsilon E} + \frac{\sigma_y}{E}, \; 2\epsilon_x = \frac{\sigma_x}{E} + \frac{-\upsilon\sigma_y}{E}$$

simplify,

$$\epsilon_y = \frac{1}{2E}(\sigma_y - \frac{\sigma_x}{\upsilon}), \; \epsilon_x = \frac{1}{2E}(\sigma_x - \frac{\upsilon}{\sigma_y})$$

$$\epsilon_y = \frac{1}{E}\sigma_y$$

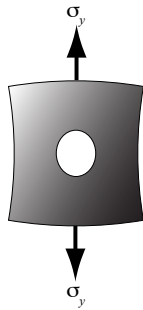$$\epsilon_x = \frac{-\nu}{E}\sigma_y$$

(2)

Figure 8 Schematic of strain resulting from a uniaxial stress applied along the *y*-direction as illustrated for a plate with a through-hole. The *x*-direction is horizontal.
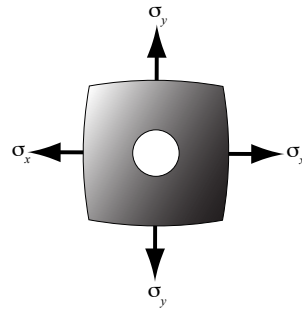

Figure 9 Schematics of solid plate with through-hole subjected to biaxial state of stress

5 Conclusions

6 References