LAB NO 2
WORK HARDENING AND ANNEALING OF COPPER

Lab 2: Work Hardening and Annealing of Copper

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Purpose: To study the correlation of hardness and the amount of cold-work in a deformed, annealed copper specimen.

Theory:

hardness: a measure of a material's resistance to localized plastic deformation.

Strain hardening (i.e. work hardening): the phenomenon whereby a ductile metal becomes harder and stronger as it is plastically deformed.

Annealing: a heat treatment wherein the microstructure and, consequently, the properties of a material are altered.

"Annealing" frequently refers to a heat treatment whereby a previously cold-worked metal is softened by allowing it to re-crystallize.

Apparatus

Rolling mill (see fig. 1)
Copper test specimen (see Fig 2)
Sand paper
micrometer
Rockwell hardness tester

Procedure:

1. Removed the scale and dirt on the specimen using sandpaper to give it a smooth even finish.

2. Checked the offset on the micrometer and found it to be 0.022 mm. (.04 Check this?)

3. Marked test specimen in three locations (i.e. two ends and center) in order to measure its dimensions in the same place each time. (See fig. 2).

4. Measured the height and width of the specimen at these locations with the micrometer before beginning the testing. (Note: specimen has already been annealed).

5. Turned the center cog wheel on the rolling mill counterclockwise to close the gap between the rollers and checked to see if the rollers were parallel.

Fig 1 Rolling Mill

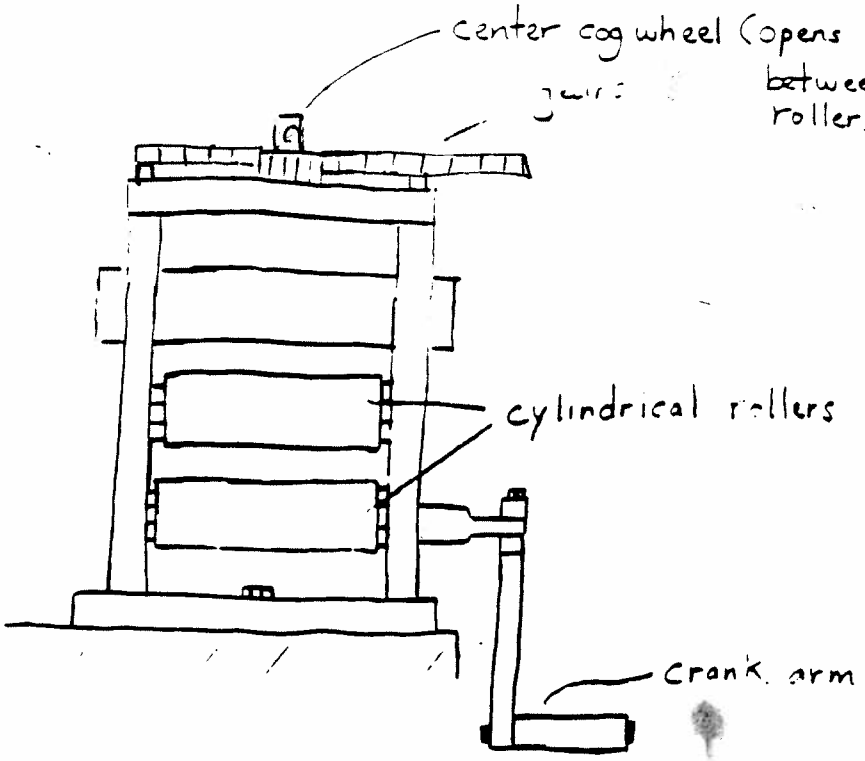
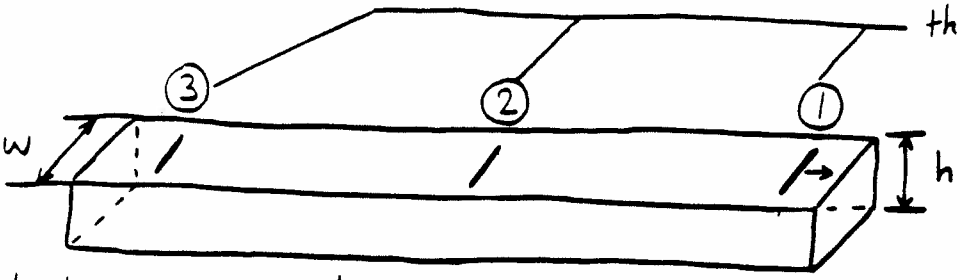


Fig 2 Copper test specimen



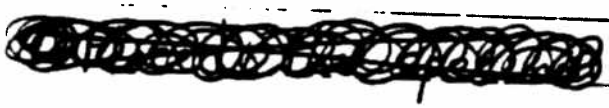
Initial Measurements:

	height, h	width, w
①	~~6.324 mm~~ 5.808	~~6.016 mm~~ 5.736 mm
②	~~6.116 mm~~ 5.801	6.126 mm
③	~~6.324 mm~~ 5.805 mm	6.132 mm

6. Removed the center cog wheel from the rolling mill and adjusted the rollers until they were parallel by turning the other two gears.

7. Replaced the center cog wheel into the rolling mill and opened the rollers such that the copper specimen was gently gripped by the rollers. Removed the specimen from the rollers.

8. Turned the center cog wheel on the rolling mill counterclockwise until the pointer on the larger gear indicated that it had rotated by one tooth.



9. Placed the end of the specimen marked with an arrow into the rollers and turned the crank arm of the rolling mill until the specimen had completely passed through the rollers. Re-measured the dimensions along the length of the specimen.

10. Placed the end of the specimen marked with an arrow into the Rockwell hardness tester, near the first marked location, the specimen by gripping between the indenter and the anvil perpendicular to the height with the three marked locations facing upwards by turning the handwheel clockwise. Continued to turn the handwheel until the pointers on the scale were at zero, then the crank handle was released. When the pointers stopped turning, the crank handle was turned forward so that the pointer gave a reading in the R_f scale. This reading was recorded.

11. Step 10 was repeated near each of the other two marked locations along the length of the specimen, (i.e. pass 1 completed).

12. Repeated steps 8 through 11 twice more, remembering to re-measure the dimensions of the specimen after each pass through the rolling mill. (i.e. for passes 2 & 3). Note: the orientation of the bar was kept the same for each pass and the hardness was

tested at [redacted] different locations surrounding the three previously marked locations on the top surface of the specimen

13. Turned the center cog wheel on the rolling mill counterclockwise until the pointer on the larger gear indicated that it had rotated by two teeth.

14. Steps 9., 10., 11., and 13 were repeated [redacted] seven times (i.e. passes 4-10).

15. Turned the center cog wheel counterclockwise until the pointer on the larger gear indicated that it had rotated by three teeth.

16. Repeated steps 9. through 11., (i.e. pass 11 completed)

17. Turned the center cog wheel counterclockwise until the pointer on the larger gear indicated that it had rotated by four teeth.

18. Steps 9., 10., 11. [redacted] and 17. were then repeated twice, [redacted] (i.e. for passes 12 + 13).

19. Placed specimen in a furnace for 15 minutes at 658°C (on dial) with a furnace [redacted] temperature of 650°C. Cooled specimen in water.

20. Repeated steps 10. and 11.

Note: Copper specimen was deformed until its [redacted] height was 10% smaller

Check

V.

Results :

Table 1 : Measurements and Reading:

No. of Passes	Height (mm)	Width (mm)	Hardness Test (R_f)
Before ①	6.324	6.016	20
" ②	6.316	6.126	20
" ③	6.324	6.132	20
Pass 1 ①	6.324	6.018	14
" ②	6.314	6.126	20
" ③	6.320	6.126	22
Pass 2 ①	6.310	6.010	25
" ②	6.318	6.122	33
" ③	6.322	6.130	54
Pass 3 ①	6.314	6.008	20
" ②	6.306	6.158	34
" ③	6.318	6.136	36
Pass 4 ①	6.300	6.026	51
" ②	6.306	6.162	47
" ③	6.312	6.134	47
Pass 5 ①	6.268	6.040	60
" ②	6.302	6.156	36
" ③	6.316	6.138	25

Table 1 : Continued

No. of Passes	Height (mm)	Width (mm)	Hardness Test (R_A)
Pass 6 ①	6.252	6.046	60
" ②	6.268	6.142	52
" ③	6.252	6.166	57
Pass 7 ①	6.228	6.048	60
" ②	6.252	6.174	50
" ③	6.196	6.176	66
Pass 8 ①	6.154	6.064	67
" ②	6.152	6.182	71
" ③	6.188	6.174	67
Pass 9 ①	6.096	6.089	69
" ②	6.136	6.196	69
" ③	6.136	6.194	71
Pass 10 ①	6.086	6.038	74
" ②	6.098	6.210	69
" ③	6.032	6.234	73
Pass 11 ①	5.936	6.166	74
" ②	6.036	6.240	74 ✓
" ③	6.014	6.242	77
Pass 12 ①	5.800	6.722	78
" ②	5.826	6.794	77
" ③	5.852	6.808	76

Table 1 Continued

No of Passes	Height (mm)	Width (mm)	Hardness Test (R_f)
Pass 13 ①	5.746	6.750	79
②	5.734	6.824	78
③	5.740	6.816	80

After furnace readings (re-annealing)

Hardness Test (R_f)	
①	13
②	18
③	21

Calculations:

Table 2: Measurements and Readings (adding the micrometer offse

No. of Passes	Height (mm)	Width (mm)	Hardness Test (R_f)
Before ①	6.346	6.038	20
②	6.338	6.148	20
③	6.346	6.154	20
Pass 1 ①	6.346	6.040	14
②	6.336	6.148	20
③	6.342	6.148	22
Pass 2 ①	6.332	6.032	25
②	6.340	6.144	33
③	6.344	6.152	54
Pass 3 ①	6.336	6.030	20
②	6.328	6.180	34
③	6.340	6.158	36

Table 2: Continued

No. of Passes		Height (mm)	Width (mm)	Hardness Test (R_F)
Pass 4	①	6.322	6.048	51
	②	6.328	6.184	47
	③	6.334	6.156	47
Pass 5	①	6.290	6.062	60
	②	6.324	6.178	36
	③	6.338	6.160	25
Pass 6	①	6.274	6.068	60
	②	6.290	6.164	52
	③	6.274	6.188	57
Pass 7	①	6.250	6.070	60
	②	6.274	6.196	50
	③	6.218	6.198	66
Pass 8	①	6.176	6.086	67
	②	6.174	6.204	71
	③	6.210	6.196	67
Pass 9	①	6.118	6.111	69
	②	6.158	6.218	69
	③	6.158	6.216	71
Pass 10	①	6.108	6.060	74
	②	6.120	6.232	69
	③	6.054	6.256	73
Pass 11	①	5.958	6.188	74
	②	6.058	6.262	74
	③	6.036	6.264	77
Pass 12	①	5.822	6.744	78
	②	5.848	6.816	77
	③	5.874	6.830	76

Table 2: Continued

No. of Passes	Height (mm)	Width (mm)	Hardness Test (R_F)
Pass 13 ①	illegible	illegible	79
②	illegible	illegible	78
③	illegible	6.838	80

After furnace readings (re-annealing)

No. of Passes	Height (mm)	Width (mm)	Hardness Test (R_F)
Did not use rolling mill after furnace: ①			13
②			18
③			21

Note: Rockwell Hardness scale F was used with a $\frac{1}{16}$ in. ball indenter, a minor load of 10 kg, and a major load of 60 kg.

Table 3: Data for plotting hardness versus change in height of copper specimen.

	{Y-axis}	{x-axis}
No. of Passes	Average Height (mm)	Average Hardness (R_F)	Change in Height (mm)
Before	6.343	20	0
Pass 1	6.341	19	0.002
Pass 2	6.339	37	0.004
Pass 3	6.335	30	0.008
Pass 4	6.328	48	0.015
Pass 5	6.317	40	0.026
Pass 6	6.279	56	0.064
Pass 7	6.247	59	0.096
Pass 8	6.187	68	0.156
Pass 9	6.145	70	0.198

Table 3 : Continued

No. of Passes	Average Height (mm)	Average Hardness (Rf)	Change in Height (mm)
Pass 100	6.084	78	0.889
Pass 110	6.017	78	0.826
Pass 18	8.848	77	0.888
Pass 18	8.762	78	0.881
Furnace		117	—

Discussion of Uncertainties :

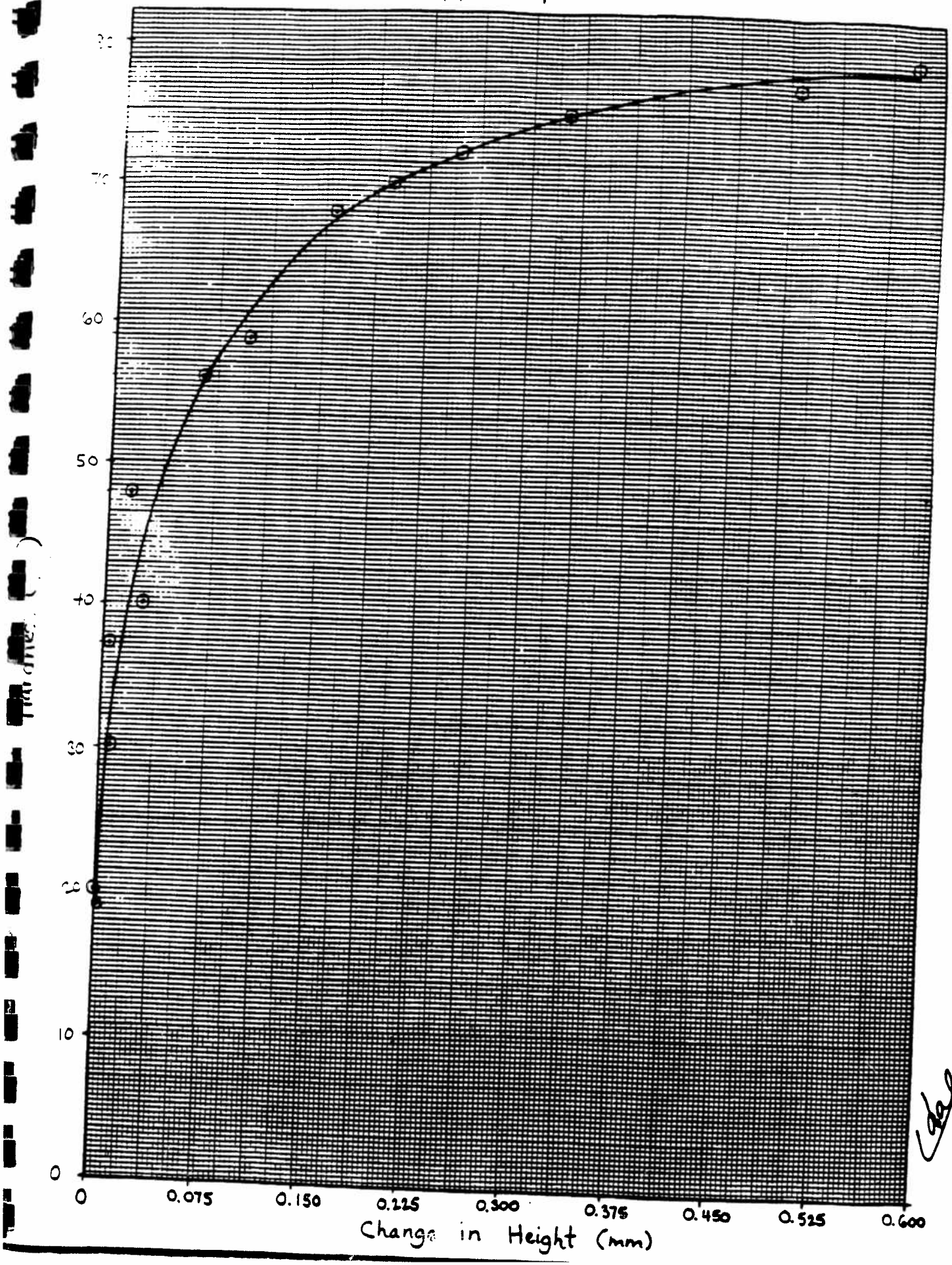
Instrument Uncertainties

The instrument errors are uncertainties caused by limitations in the calibration of the instruments used in this experiment. The micrometer, for example, has an error of ± 0.0001 mm, and an offset of 0.022 mm. The Rockwell hardness tester creates uncertainties also. As hardness values drop below 20 or rise above 100, they become inaccurate.

Object Uncertainties

The copper test specimen may not have had a constant cross-sectional area along the length of the specimen. Thus, causing variations in the hardness measurements at each marked location on the specimen. For example, one end of the specimen may have been larger than the other, causing it to be more cold-worked than the smaller end during each pass through the rolling mill.

Hardness versus Change in Height of Copper Specimen



Use Uncertainties

Use uncertainties are created by the persons conducting this experiment. For instance, the indentations (by the Rockwell hardness tester) may have been made too close to the specimen's edge and the indentations may have been made too close to each other, thus causing inaccuracies in hardness measurements.

Conclusion:

From the graph plotted of hardness versus change in height (opposite page 28), it can be seen that the greatest increase in hardness occurs between when the specimen is at its original height and when the specimen has decreased in height by 0.156 mm (≈ 2.5% of its original height). The hardness values tend to level off between the decreased changes in specimen height of 0.156 mm and 0.581 mm (i.e. between decreases of 2.5% - 10% of the specimen's height). Overall, it can be concluded that the hardness of the copper specimen increased steadily as a result of the cold-working performed on it. However, it is also concluded that the hardness of the copper specimen decreased at a phenominal rate by allowing it to re-anneal in a furnace at a temperature of approximately 650°C for 15 minutes and then cooling it rapidly in water. Thus, it was softened due to re-crystallization.