Effects of Process Annealing on Mechanical Properties of Strain-Hardened Copper: A Case of Kabel Metal Nigeria Limited.

O.S. Olokode, M.Sc.*, B.O. Bolaji, Ph.D., and O. Aiyedun, Ph.D.

Department of Mechanical Engineering, University of Agriculture
PMB 2240, Abeokuta, Nigeria.

*E-mail: Engr Olokode@yahoo.com
Bobbolaji2007@yahoo.com
laiyedun 494@yahoo.com

ABSTRACT

This paper reports the results of an investigation carried out on the effects of process annealing on the mechanical properties of strain-hardened copper from Kabel Metal Nigeria Limited. The cold-rolled copper samples, at different degrees of deformation, were annealed and their mechanical properties such as ultimate tensile strength, impact, hardness, percentage reduction in area, and percentage elongation were observed after cold working and annealing. The results obtained showed that the hardness of copper during cold rolling increases with the degree of deformation due to strain hardening. The maximum value of hardness obtained from cold-rolled copper was 117 HB at 40% reduction in area, while the average hardness values obtained after annealing temperatures of 300 °C, 400 °C and 500 °C were 79.2, 67.2 and 45.7 HB, respectively. During tensile test, the material fractured with very little elongation at 35% reduction in area. The maximum ultimate tensile stress obtained was 188.4 N/mm^2 at 20% reduction in area. Anneal strengthening effect was observed in the copper. The amount of strengthening effect increases with increasing degree of prior cold work. For the optimum combination of desired mechanical properties, copper wire should not be strain hardened beyond 20% reduction in cross-sectional area without been critically annealed before any further deformation.

(Keywords: annealing, cold-rolling, copper, deformation, mechanical properties, strain hardening)

INTRODUCTION

The deformation of metals at room temperature is accommodated by layers of atoms sliding over one another within the crystal grains of the metal. As this sliding occurs, the metal grains become distorted, the atom layers buckle, and there is a rapid increase of small regions of atomic dislocations within the grains (Zerilli and Armstrong, 1987; Fonteyn and Pitsi, 1990; Callister, 2007). Because of the distortion and increase in dislocation density, it becomes more and more difficult for the dislocation to move through the existing forest of dislocation and thus the metal work or strain hardens with increased cold hardening. If this deformation or cold working is continued sufficiently, even ductile metals such as copper will become brittle and crack during the deformation (Follansbee and Kocks, 1988; Nestorovic and Tancic, 2002).

According to Kouzeli and Mortensen (2002), the size parameter characteristics of a material's microstructure can exert a strong influence on its mechanical properties, most of these size effects come about because of the constraint to which a particular deformation mechanism is being subjected. Lattice dislocations are forced by the micro-structural constraint to bow out or pile up, and their movement requires an external stress dependent on a micro-structural parameter (Mimura et al., 1997; Majta and Zurek; 2003; Majta et al., 2005).

Copper has excellent conductivity, but has poor resistance to softening at moderate temperatures (Hust and Lankford, 1984). This presents a considerable problem to engineers and designers of electrical equipment. One of the mechanisms employed to improve the mechanical properties of copper is anneal hardening, whereby considerable strengthening is attained when copper in cold-rolled state is heat treated (Rajan and Sharma, 1988; Nestorovic et al., 2003; Nestorovic, 2004).

The results of the effect of strain hardening on copper during cold rolling require a decrease in reduction rate, and the maximum reduction of copper wire prior to process annealing needs to be established as a factor of safety during design for plastic deformation. Therefore, the objective of this research work is to study experimentally, the effects of process annealing on the mechanical properties of strain-hardened copper during plastic deformation using Kabel Metal Nigeria Limited as a case study.

MATERIAL METHODS

Basic Theory

Copper like most deformable metals can be rolled, extruded, drawn, pierced, etc. during plastic deformation which involves stressing the metal beyond its elastic limit, thus giving rise to movement of dislocations. As deformation is continued, there is a continual increase in the number of dislocations existing per unit area of the metal. This simply implies that the more the deformation, the higher the dislocation density and this gives rise to grain boundaries impeding the movement of these dislocations. As a result, higher levels of applied stress will be required to continue the deformation process.

One of the major effects of continuing the deformation process is the increase in hardness of metal as the crystal grains of the original metal become distorted and fragmented. This phenomenon is known as work/strain hardening (Guy and Hren, 1994; Rollason, 1996).

The strain hardening relationship of copper wire can be measured by the changed in its ultimate tensile strength (UTS) as against the percentage reduction in cross sectional area (degree of deformation).

$$\%\ \text{Reduction in cross-sectional area} = \frac{A_o - A}{A_o} \times 100\% \qquad \textbf{(1)}$$

where, A_0 = initial area (m^2)
A = the value of area at required reduction (m^2).

The hardness number is a function of both the magnitude of the load and the diameter of the resulting indentation (Equation 2).

$$HB = \frac{2P}{\pi D\left[D - \sqrt{\left(D^2 - d^2\right)}\right]} \qquad \textbf{(2)}$$

where, HB = Brinell hardness number
P = applied load (kg)
D = diameter of specimen (mm)
d = indentation diameter (mm)

Materials and Its Source

Kabel Metal Nigeria Limited, the producer of various sizes of wires and cables was used as the case study for this research. The copper materials used were of relatively high purity and they were obtained from this company. They were in form of wire cables and the amount was 50 kg, which was later melted and cast into ingot size (150 x 30 x 15 cm) via cope and drag method, and milled to 100 x 10 x 10 cm.

Experimental Work

In the experimental work, the mechanical properties of the copper sample were evaluated after two stages of processing. The first is carried out after the copper samples have been cold rolled to different degrees of reduction in cross sectional area, while the second check is carried out after the cold rolled samples have been heat treated.

Experimental Procedures

Charging: The copper cables were carefully cut into small bits to facilitate their being fed into the crucible furnace utilized for the melting charge.

***Melting*:** The copper cable being charged into furnace is allowed to melt completely and given an amount of superheat of about 300 – 500 $^{\circ}$C above the material melting point. Then at that temperature, the molten metal was poured into the feed of the locked cope and drag, and left to solidify, and the adjourning parts were cut off.

Machining: The sample was machined to specification on the center lathe machine via turning and milling operations. The cold rolling process was carried out via the use of a rolling press, and the dimensions of the specimen are taken with the aids of vernier caliper before and after each run through the rolling press. The cross sectional area is calculated to ascertain the percentage reduction (5%, 10%, 15%, 20%, 25%, 30%, 35% and 40%).

Hardness Test: Hardness tests were carried out using a Brinell Hardness Tester. Each specimen was tested 5 times and the average hardness value was obtained. Diameter of indentation is measured with a special low-power microscope utilizing a scale that is etched on the eyepiece. The total number of test specimens used was 36 (i.e. 9 cold rolling and 9 for each temperatures of annealing 300 °C, 400 °C and 500 °C).

Tensile Test: Universal testing machine (Hounsfield Tensometer) was used for the determination of the respective ultimate tensile strength load. A standard 2-ton load was used and the total number of test pieces used was four. The tensile strength, elongation and percentage reduction in area were read from the digital display attached to the machine.

Annealing: The process annealing was performed on the test piece in a metallurgical furnace of 1000 °C capacity. The copper cable wires that have been strain hardened at various percentages of reduction in cross sectional area were annealed at temperatures 300 °C, 400 °C and 500 °C. The test pieces were heated at the furnace rate and soaked for 15 minutes at the attainment of the required varying temperatures. Hardness and impact test were carried out on the annealed test pieces.

Impact Test: The specimen was milled, notched and the energy absorbed in fracturing was measured. The total number of specimen tested was 14 (7 before and 7 after annealing to 500 °C).

RESULTS AND DISCUSSION

The results obtained give an estimated behavioral pattern of the various cold worked samples of copper cable wires from Kabel Metal Nigeria Limited before and after heat treatment. During cold rolling process, it was observed that the specimen have increasingly roughened surfaces as the degree of cold rolling increased, due to dislocation pile up at the grain boundaries.

Tables 1 and 2 show different initial area of specimen prepared for hardness, tensile and impact tests and their percentage reduction in area as against the estimated value and value obtained experimentally. The hardness of the copper samples during cold rolling increases with increase in the reduction in cross-sectional area (degree of deformation) due to strain hardening (Figure 1). The maximum value of hardness obtained was 117 HB at 40% reduction in area.

Table 1: Final Area of Copper Wire Specimens during Hardness Test with Initial Area $A_0 = 100\ mm^2$

Reduction in Area (%)	Final Area of Specimen (mm^2)	
	Estimated	Experimental
5	95.00	94.90
10	90.00	89.60
15	85.00	84.00
20	80.00	79.80
25	75.00	74.90
30	70.00	70.20
35	65.00	64.70
40	60.00	59.90

Figure 2 shows the variation of ultimate tensile strength of cold-rolled copper samples with degree of deformation. From the figure, the ultimate tensile strength value first increased as percentage reduction in area increased up to 20% and thereafter decreases with increased percentage reduction in area of specimen. It was observed that the material fractured with very little elongation at 35% reduction in area (Table 2), this was due to the fact that the material had lost its ductility from cold rolling process.

Figure 3 shows the dependence of hardness on degree of deformation for copper samples with annealing temperatures of 300 °C, 400 °C, and 500 °C. The hardness values increase as the percentage reduction in area increases, but decrease as the annealing temperature increases. During annealing of the samples after cold rolling, the hardness value reduces with increase in annealing temperature due to recovery and re-crystallization. The average hardness values of cold-worked samples at annealing temperatures of 300 °C, 400 °C, and 500 °C are 79.2, 67.2 and 45.7 HB, respectively.

Table 2: Tensile Test Values of Copper Wire with Initial Area of 48 mm^2 and Gauge Length of 20 mm.

Reduction in Area (%)	Final Area of Specimen (mm^2)		Ultimate Load (kg)	Elongation (mm)	
	Estimated	Experimental		Before Test	After Test
5	45.60	45.20	720	21.2	21.6
10	43.20	43.34	770	21.6	22.1
15	40.80	40.93	780	21.9	22.2
20	38.40	38.53	740	22.1	22.3
25	36.00	36.11	670	22.6	22.9
30	33.60	33.69	530	23.0	23.1
35	31.20	31.30	370	23.6	23.6

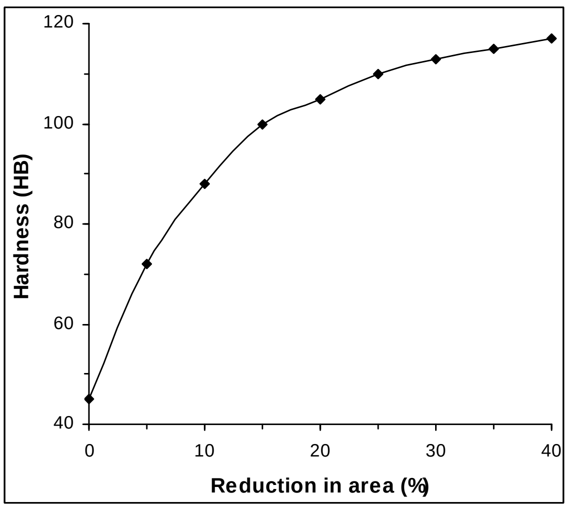

Figure 1: Variation of hardness of Cold-Rolled Copper Samples with Percentage Reduction in Area.

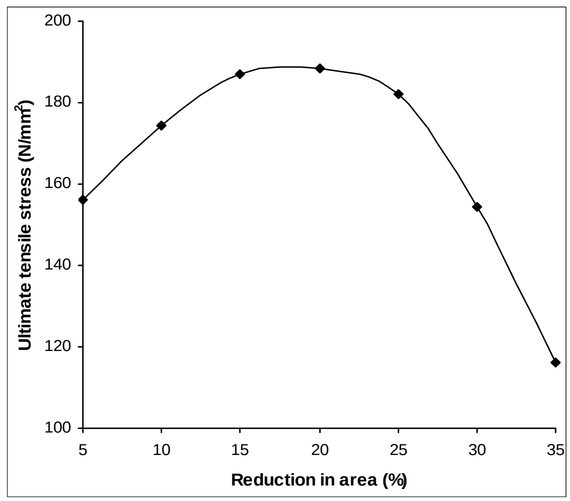

Figure 2: Variation of Ultimate Tensile Stress of Cold-Rolled Copper Samples with Percentage Reduction in Area.

Figure 4 shows the actual impact values versus percentage reduction in area at annealing temperatures of 500 °C. As shown in the figure, increase in amount of cold work (degree of deformation) lowered energy value on impact, whereas the impact test of the cold worked samples after annealing up till 500 °C, required higher energy to fracture with increased cold work (Figure 4). Therefore, anneal strengthening effect (toughness) of the material increased with increase in degree of prior cold work and corresponding annealing.

CONCLUSION

The effects of process annealing on the mechanical properties of strain hardened copper from Kabel Metal Nigeria, Ltd., Ogba-Ikeja was investigated after two stages of processing. The first is carried out after the copper samples have been cold rolled to different stages of reduction in cross sectional area, while the second is carried out after the cold rolled samples have been heat treated.

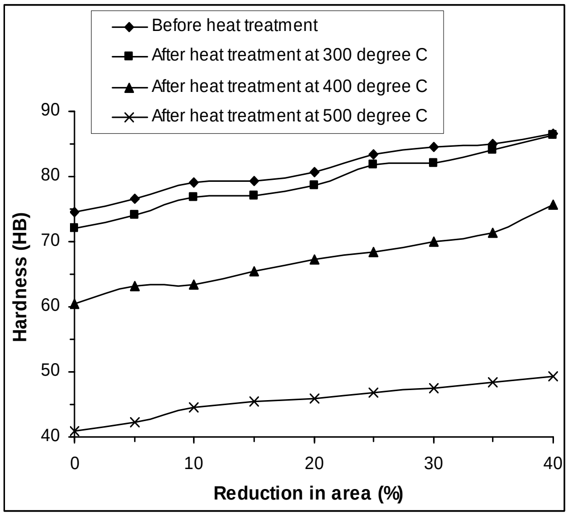

Figure 3: The Change of Hardness of Cold-Rolled Copper Samples with Percentage Reduction in Area at Different Annealing Temperatures.

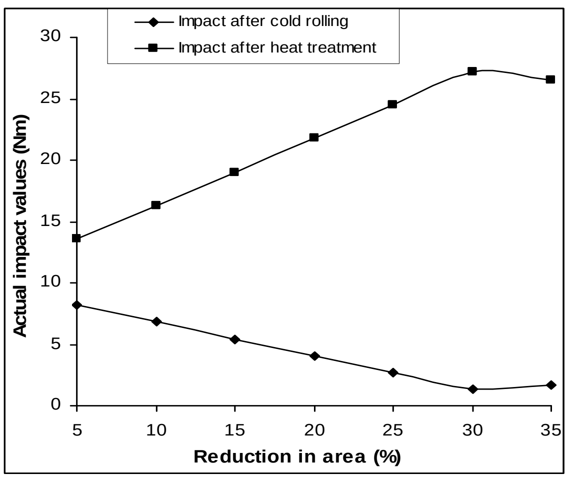

Figure 4: Actual Impact Values versus Percentage Reduction in Area at Annealing Temperature of 500 °C.

The results obtained give an estimated behavioral pattern of the various cold worked samples of copper cable wires before and after heat treatment. The hardness of the copper during cold rolling increases with degree of deformation due to strain hardening. The maximum value of hardness obtained from cold-rolled copper was 117 HB at 40% reduction in area, while the average hardness values obtained after annealing temperatures of 300 °C, 400 °C, and 500 °C were 79.2, 67.2 and 45.7 HB, respectively.

During tensile test, the specimen fractured with very little elongation, this was due to the fact that the material had lost its ductility from cold rolling process. The maximum value of ultimate tensile stress obtained from cold-rolled copper was 188.4 N/mm^2 at 20% reduction in area. Also, increase in amount of cold work lowered energy value on impact, whereas the impact test of the cold worked samples after annealing up till 500 °C, required higher energy to fracture with increased cold work, which shows anneal strengthening effect in the copper. The amount of strengthening effect increases with increasing degree of prior cold work. For the optimum combination of desired mechanical properties, copper wire should not be strain hardened beyond 20% reduction in cross-sectional area without been critically annealed before any further deformation.

REFERENCES

1. Callister, D.W. 2007. *Materials Science and Engineering: An Introduction*. 7th Edition. John Wiley and Sons, Inc.: New York, NY.

2. Follansbee, P.S. and Kocks, U.F. 1988. "A Constitutive Description of the Deformation of Copper Based on the use of the Mechanical Threshold Stress as an Internal State Variable". *Acta Metallurgical*. 36:81 – 93.

3. Fonteyn, D. and Pitsi, G. 1990. "Inelastic Scattering in Thermal Transport Properties of Deformed Copper Single Crystals". *Journal of Low Temperature Physics*. 80:325 – 332.

4. Guy, A.G. and Hren, J.J. 1994. *Elements of Physical Metallurgy*. 5th Edition. Addison-Wesley Publishing Company: Los Angeles, CA.

5. Hust, J.G. and Lankford, A.B. 1984. *Thermal Conductivity of Aluminum, Copper, Iron and Tungsten for Temperatures from 1 K to the Melting Point*. National Bureau of Standards: Boulder, CO. NBSIR 84-3007.

6. Kouzeli, M. and Mortensen, A. 2002. "Size Dependent Strengthening in Practice Reinforced Aluminum. *Acta Metallurgical*. 50:39 – 51.

7. Majta, J., Stefanska-Kqdziela, M. and Muszka, K. 2005. "Modeling of Strain Rate Effects on Microstructure Evolution and Mechanical Properties of HSLA and IF-Ti Steels". The 5th International Conference on HSLA Steels. 8 – 10 November, 2005. Sanya, Hainan, China. pp. 513 – 517.

8. Majta, J. and Zurek, A.K. 2003. “Microstructure and Deformation of Microalloyed Steels in the Two-Phase Region”. In: EPD Congress 2003 of the Extraction and Processing Division of the Minerals, Metals and Materials Society. Schlesinger, M.E. (ed.). TMS: San Diego, CA. pp. 63 – 81.

9. Mimura, K., Ishikawa, Y., and Isshiki, M. 1997. “Precise Purity-Evaluation of High-Purity Copper by Residual Resistivity Ratio”. *Materials Transactions*. 38:714 – 722.

10. Nestorovic, S. 2004. “Influence of Deformation Degree at Cold-Rolling on the Anneal Hardening Effect in Sintered Copper-Based Alloys”. *Journal of Mining and Metallurgy*. 40(1):101 – 109.

11. Nestorovic, S., Ivanic, L., and Markovic, D. 2003. “Influence of Time of Annealing Hardening Effect of Cast CuZn Alloy”. *Journal of Mining and Metallurgy*. 39(3 & 4):1 – 10.

12. Nestorovic, S. and Tancic, D. 2002. “Anneal Strengthening Effect in Sintered Copper-Based Alloys”. International Conference on Deformation and Fracture in Structural PM Materials. Slovakia. 144 – 151.

13. Rajan, T.V. and Sharma, C.P. 1988. *Heat Treatment Principles and Techniques.* Prentice Hall: New Delhi, India.

14. Rollason, E.C. 1996. *Metallurgy for Engineers*. 5th Edition. Edward Arnold Publishers: New York, NY.

15. Zerilli, F.J. and Armstrong, R.W. 1987. “Dislocation-Mechanics-Based Constitutive Relations for Material Dynamics Calculations. *Journal of Applied Physics*. 61:1816 – 1825.

ABOUT THE AUTHORS

Engr. O.S. Olokode is a Lecturer in the Department of Mechanical Engineering, Federal University of Agriculture, Abeokuta, Nigeria. Engr. Olokode is a registered Engineer and is also a member of the Nigeria Society of Engineers. He holds a Master of Science (M.Sc.) in Metallurgy and Material Engineering. He is currently about to defend his Ph.D. Thesis. His research interest is in the area of Material Engineering.

Engr. (Dr.) B.O. Bolaji is a Lecturer I in the Department of Mechanical Engineering, Federal University of Agriculture, Abeokuta, Nigeria. Engr. Bolaji is a registered Engineer and is also a member of the Nigeria Society of Engineers. He holds a Ph.D. degree in Thermofluids. His research interests are in the areas of thermofluids, energy, heat transfer, and environmental engineering.

Prof. P. O. Aiyedun is a Professor of Mechanical Engineering, Federal University of Agriculture, Abeokuta, Nigeria. Prof. Aiyedun is a registered Engineer and is also a Fellow of the Nigeria Society of Engineers. He holds a Ph.D. in Metallurgy and Material Engineering. He is currently the Dean, College of Engineering, Federal University of Agriculture, Abeokuta, Nigeria. His research interest is in the area of production and material engineering.

SUGGESTED CITATION

Olokode, O.S., B.O. Bolaji, and O. Aiyedun. 2008. “Effects of Process Annealing on Mechanical Properties of Strain-Hardened Copper: A Case of Kabel Metal Nigeria Limited.. 9(2):278-283.

Pacific Journal of Science and Technology