Influence of a cold deformation process by drawing on the electrical properties of copper wires

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Abstract

This article presents a study of the drawing, deformation, hardening and heat treatment of copper wire, in order to investigate the influence of combinations of operating variables (annealing factor, oil emulsion temperature and machine speed) during the drawing process on the electrical conductivity of copper wires. The results showed that when the metal is deformed, the value of electrical conductivity suffers a decrease due to the hardening phenomenon. Because of this, it is necessary to heat treat the material. So, it was observed that the annealing factor, which is associated with the thermal treatment temperature, showed a high degree of correlation with the electrical conductivity. This fact is explained by the annealing factor which is responsible for the intensity of the heat treatment. The speed at which the drawing occurs also showed a direct correlation with electric conductivity because the higher the value, the greater the heat treatment temperature and consequently, the greater the electrical conductivity of the material.

On the other hand, it had not been possible to establish a conclusion about the correlation between the electrical conductivity and oil emulsion temperature during the drawing process.

Keywords: deformation, drawing, heat treatment, copper wires.

1. Introduction

The prediction of copper wire electrical properties through plastic deformation resulting from the drawing process, represents a theme with great potential for the industries that operate in the field of electrical conductors. However, for an effective control of the electrical conductivity of copper wires, it is necessary to develop a study of the main process variables that affect this activity. In this sense, a research of the industrial process must include several factors, such as: drawing analysis with the oil emulsion temperature of the drawing machine at high and low temperatures; the effect of heat treatment temperature on the material; and the material response behavior during the drawing process, occurring at different speeds. Within this context, the influence of cold deformation process for drawing was analyzed in this study with the objective of investigating the influence of combinations of operating variables (annealing factor – AF, Oil emulsion temperature - OET and machine speed - MS) during the drawing process on the electrical conductivity of copper wires.

2. Material and method

According to ASTM B193, for measuring the electrical conductivity of copper, the sample has to initially present an 8.00mm diameter (copper rods), which after the drawing process, is reduced to 2.00mm.

For the experimental part of this task, the controlled variables in the industrial process (annealing factor-AF; oil emulsion temperature-OET and machine speed-MS) have been correlated through a factorial experimental planning. Such planning predicted 8 distinct combinations for the variables under study.

In total, 8 runs and 4 combinations of process variables for each of the races were accompanied, resulting in a total of 32 samples. Each run refers to copper rods drawn in 8 different process combinations. Table 1 shows the results of the factorial experimental planning, containing the values for the three variables used in the study, for each one of the 8 combinations.

Process Combination	Annealing Factor - AF (%)	Oil Emulsion Temperature - OET (°C)	Machine Speed - MS (m/s)
1	90	40	16
2	90	20	16
3	90	40	8
4	90	20	8
5	10	20	16
6	10	20	8
7	10	40	16
8	10	40	8

Table 1
Result of factorial planning.

The oil used was Agefil E-505N from Agena and the drawing process was conducted in a Samp, Model MS 400 primary drawing machine, enabling a 30% elongation and reduction in an area of 23% on each die. This drawing machine was assembled for this research with a total of 10 dies. The dies used were polycrystalline diamond and are shown in Table 2 below.

Dies (mm)	Reduction (%)
6.63	23
5.81	23
5.10	23
4.47	23
3.91	23
3.43	23
3.00	23
2.63	23
2.31	23
2.03	-

Table 2
Dies and reduction by pass used during the drawing.

After the drawing process, the 32 samples under study underwent the following steps:

a) Microscopic Analysis

• First, a manufactured Buehler cutting machine for working with non-ferrous metal was used

• Then, the samples were sanded (3 Silicon Carbide sandpaper with grits of 320, 500 and 1200) with the aid of a Buehler machine at a speed of 100 RPM, whereby water was used for cooling during this activity.

• Mechanical polishing was carried out on the samples and used a special alumina metallographic cloth (1 layer to 0.5μ).

• A solution of Ferric Chloride for the chemical attack on the samples was used.

• After the chemical attack of the samples, they were taken to the microscope provided by Nikon, with capability of increasing from 10 to 1000 times (in the case of the analysis of the grains of this document, we used the 200 times zoom).

b) Analysis of Electrical Conductivity

• According to the standard IEC 60811-1-NBRNM-1 27, measurements of the diameter of the samples were made using a Mitutoyo micrometer with millesimal scale accuracy.

• Mass measurement of the samples was carried out with the aid of a Gehaka analytical balance, with centesimal precision. Samples were cut into a 195cm length, due to the requirement of AESA bridge device used for determining the electrical resistance of the samples under study.

• According to ASTM B193, samples were kept in an oven for a period of 30 minutes at a temperature of 500°C.

• Then the pickling of the samples was carried out using a nitric acid solution, in order to eliminate the superficial oxidation of specimens. This step is very important because if it is not performed correctly, the oxides deposited on the copper wires will cause changes in electrical resistance values.

• The tests to determine the electrical resistance, were performed using a bridge model Cortinollis EASA.

• The determination of the electrical resistivity in weight of the samples was obtained using Equation 1.

$$\rho = \frac{(R \, X \, P)}{C} \quad (1)$$

Where: ρ = Electrical resistivity in weight (Ωg/m); R = Electrical resistance of the sample (Ω/Km); P = Mass of the sample (g/m); C = Sample length (m).

• The determination of the electrical conductivity in %IACS in the samples was obtained using Equation 2.

$$\sigma = \frac{0.15328}{\rho} \quad (2)$$

Where: σ = electrical conductivity in %IACS;

0.15328 = matches the resistivity in weight of copper with conductivity 100.00% IACS.

3. Results

The annealing factor-AF (or the intensity of the thermal treatment) has a direct connection with the electric current (A) and the voltage (V) of the oven. Therefore, the higher these values, the greater the heat treatment applied to the wire. Table 3 shows the values of electrical quantities (current and voltage) that were found in the measurement of the transformer of the oven, for the different combinations of the process.

Process Combination	Process Variables AF;OET;MS	Tension (Volts)	Electric Current (Amperes)
1	90;40;16	40.6	2252.0
2	90;20;16	40.6	2252.0
3	90;40;8	28.9	1584.0
4	90;20;8	28.9	1584.0
5	10;20;16	4.4	304.0
6	10;20;8	3.1	184.0
7	10;40;16	4.4	304.0
8	10;40;8	3.1	184.0

Table 3
Electrical quantities (current and voltage) obtained during the heat treatments.

After heat treating the wires with different combinations of the process variables, the electrical conductivity values were obtained, as shown in Table 4. The original average of the 4 electrical conductivity copper rods used was 101.40% IACS.

		Electric Conductivity (%IACS)			
Process Combination	Process Variables AF;OET;MS	Run 1	Run 2	Run 3	Run 4
1	90;40;16	100.40	100.04	100.12	100.19
2	90;20;16	100.51	100.15	100.22	100.29
3	90;40;8	99.72	99.46	99.07	99.41
4	90;20;8	99.77	99.52	99.13	99.35
5	10;20;16	98.61	98.85	98.62	98.69
6	10;20;8	98.43	98.20	98.53	98.56
7	10;40;16	98.53	98.40	98.54	98.49
8	10;40;8	98.52	98.63	98.46	98.54

Table 4
Electrical conductivity values found after heat treating the wires with different combinations of process variables.

The microstructural aspect of the samples obtained under the working condition (10; 20; 8) is shown in Figure 1. The combination of this process presented the lowest values of electrical conductivity. The microstructure of the samples of the combination (90; 20; 16) that gave the highest values of electrical conductivity are presented in Figure 2.

Figure 1
Microstructural aspect of the samples obtained under the condition (10; 20; 8) Optic Microscopy (Increased 200 times).

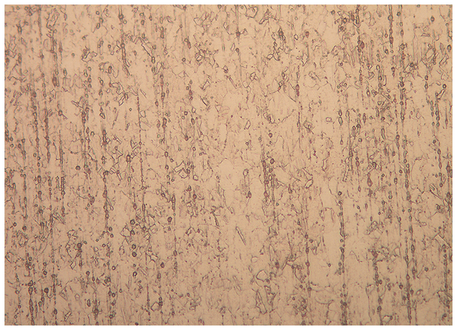

Figure 2
Microstructural aspect of the samples obtained under the condition (90; 20; 16) Optic Microscopy (Increased 200 times).

4. Discussion

Dieter (1988) argues that the modifications that occur in metals during the cold deformation process for drawing, affect the mechanical and electrical properties of the material. The changes in the structure of the metal, caused by the drawing process, are due to the material hardening phenomenon. This phenomenon occurs by reduction of the cross sectional area of the wire. In this sense, according to Reed Hill (1982), two stages occur during a heat treatment of recrystallization after drawing the material, in order to restore the electrical and mechanical properties. Namely: first stage-recovery (internal rearrangement of the microstructure) and second stage-recrystallization (recovery of the mechanical and electrical characteristics).

Padilha and Siciliano Jr. (2005) report that microstructural changes made during the first stage (recovery) of the heat treatment generate a partial recovery of the mechanical and electrical properties, while the second stage (recrystallization) extinguishes virtually all offsets and for these drawn wires, the characteristics are very close to those of the primary-state rods.

The results obtained under condition 10; 20; 8, as shown in Table 3, the heat treatment presented the lowest values of electrical conductivity. The low value of the electrical property of copper wire is justified by the lowest temperature in the thermal treatment. The microstructural aspect of samples obtained under the working condition (10; 20; 8) can be seen in Figure 1. It is noticed that the grains in Figure 1 are fully deformed in the direction of the drawing, there are large amounts of stretch marks (texture), and that the recrystallization was not complete in this sample.

This characteristic of the grain, according to Correa (2004) creates a barrier (resistance) to the movement of electrons, causing increased electrical resistance of the wire and as a consequence, its reduction in electrical conductivity.

The samples kept under higher temperature during heat treatment, showed better values of electrical conductivity, with emphasis on the combination within the process (90; 20; 16), as in Table 3. The highest values of electrical conductivity are justified by Table 3. It can be inferred that the samples kept under the highest temperature during the heat treatment presented higher values of voltage and electrical current in the oven.

Analyzing the grains of the material combination of process (90; 20; 16), Figure 2, with the highest values of electrical conductivity, it is possible to verify that the recrystallization was also not complete (presence of Stretch marks) However, the same occurred more intensely than shown in Figure 1.

This indicates, according to Correa (2004), that the current will circulate more easily through the wire due to lower electrical resistance, and this justifies the greatest results of electrical conductivity.

The conditions of the process variables (90; 20; 16) were those that resulted in a higher value of electrical conductivity (100.51%IACS). The conductivity value approached (0.89% IACS) the average value of the original electrical conductivity of 4 rods used in the study was (101.40% IACS). Therefore, the best conditions of the process variables were: (90; 20; 16).

5. Conclusion

Upon analysis of the results, it was possible to observe that the variables: annealing factor-AF (temperature of heat treatment) and the machine speed – MS were those that caused the greatest impact on the electrical properties of the copper deformed by cold drawing. In this way, the variables should be controlled and monitored during the drawing process and the heat treatment of recrystallization to ensure the largest possible values of electrical conductivity of drawn wires.

The third variable, the oil emulsion temperature - OET, presented no direct relationship with the values of electrical conductivity because they showed large oscillation.

The condition of the process that presented the largest annealing factor and the biggest drawing speed (90; 20; 16) caused the greatest value of electrical conductivity. However the recrystallization of the sample was not complete (Figure 2).

After the cold deformation process by drawing, a heat treatment is necessary to restore the electrical and mechanical properties of the material.

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