The Effect of Oxygen Content on Mechanical and Conductivity Properties of Copper Rods Produced by Contirod and Up-Cast Continuous Casting Methods

Ilkay Kinas
Er-Bakır Electrolytic Copper Products Inc.
Bozburun Road, A. Nuri Erikoglu Street, No: 29, 20085 Gumusler Denizli, Turkey
E-mail: ikinas@erbakir.com.tr

Engin Tan (Corresponding author)
Faculty of Technology, Department of Metallurgical and Materials Engineering,
Pamukkale University, Kinikli Campus, 20260 Pamukkale Denizli, Turkey
E-mail: etan@pau.edu.tr

Hilal Can
Faculty of Technology, Department of Metallurgical and Materials Engineering,
Pamukkale University, Kinikli Campus, 20260 Pamukkale Denizli, Turkey
E-mail: hilalcan@pau.edu.tr

Abstract

Many processes with technological differences are used in the production of copper wire rods. In this study, wire drawing process was applied to oxygen bearing copper (ETP-Electrolyte Tough Pitch) wire rods produced by Contirod continuous casting process, oxygen-free electrolytic copper (OFC-Oxygen Free Copper) wire rods produced by Up-Cast continuous casting method and three different alloyed copper (CuSn0.18, CuMg0.5, CuAg0.10) wire rods also produced by Up-Cast continuous casting method. Tensile and conductivity tests were carried out to determine the effect of oxygen content on mechanical properties and product quality. Microstructure investigations were also carried out to determine the metallographic properties of the produced wires. As a result of the study, it was seen that the oxygen content had significant effects on the product quality and the mechanical properties, and also the most breakage occurred in oxygen bearing copper (ETP) in wire drawing process. In the study, it was determined that the oxygen content had no effect on the conductivity properties of copper wire.

Keywords: Up-Cast casting, Contirod casting, Mechanical properties, Conductivity, Electrolytic copper rod.

1. Introduction

Today, electrolytic copper rods are used in many areas including motor coils, generators, electric train lines, transmission lines that transmit electricity to industrial zones and households, as well as aviation and aerospace industries. Copper wire production process generally includes rod production and wire drawing procedures by continuous casting. Following the wire drawing procedure, coating and bending operations are carried out according to the place of use.

In industrial applications, different processes are adopted in the production of copper rods by continuous casting methods called Southwire, Contirod and Up-Cast (Outokumpu) (Bell&Cofer, 1964; Ashton, 1974; Rantanen, 1980; Chia&Adams, 1981; Tominga&Kazhiwazaki, 1984; Nabil et al., 2016; Meshal et al, 2017). Although these processes differ technologically from each other, the two most important factors determining the quality of the products according to their place of use are the oxygen and impurity contents of the electrolytic copper (Smart&Smith, 1942; Pitt&Tayler, 1973; Armstrong-Smith, 1972;

Reese&Condra, 1969; Pastorek&Rapp, 1969; Smets&Morties, 1983; Ivanich&Kochowski, 1993; Fayaerts et al., 1996; Arıkan et al., 1994; Opie et al., 1970; Bigelow&Chen, 1976; Knych et al., 2011; Knych et al., 2010; Gao et al., 2006).

In this study, mechanical and conductivity properties of oxygen bearing copper (ETP-Electrolyte Tough Pitch) wire rod produced by Contirod continuous casting process, oxygen-free electrolytic copper (OFC-Oxygen Free Copper) wire rod produced by Up-Cast continuous casting method and copper rod with three different alloys (CuSn0.18, CuMg0.5, CuAg 0.10) produced by Up-Cast continuous casting method at Er-Bakır Electrolytic Copper Products Inc. were compared and the factors that affect the product quality were investigated.

2. Materials and Methods

In the study, 20 pieces of 8-mm-diameter alloyed, and unalloyed copper samples were taken from wire rods with different oxygen contents produced by Contirod and Up-Cast continuous casting method and the oxygen contents of these samples were determined using Leco oxygen detection device found in Er-Bakır Electrolytic Copper Products Inc. according to the ASTM B-49 standard. Table 1 shows the average oxygen contents of the samples. Copper rods with different oxygen contents were drawn in Niehoff wire drawing machine found in Er-Bakır Electrolytic Copper Products Inc. at room temperature and wires with diameters of 0.187 - 0.207 mm were produced to determine their cold deformation behaviors.

Table 1. Average oxygen contents of copper rods used in experiments

Sample	ETP		OFC		CuSn0.18		CuMg0.5		CuAg0.10	
Oxygen content (ppm)	227.36		2.77		3.0		2.04		2.97	
Standard and range	ASTM B-49	100-600	ASTM B-49	0.1-5	ASTM B-49	0.1-5	ASTM B-49	0.1-5	ASTM B-49	0.1-5

The wire drawing machine features an automatic annealing unit after the cold drawing unit. The annealing process is carried out by passing the rod that reached its final diameter by passing through the wire drawing molds continuously through the rollers called the annealing band, and the electric current applied to the band ensures continuous annealing after the wire is drawn.

In the study, tensile strength tests were performed to determine the mechanical properties of the produced wires. Tensile strength tests were carried out in a Zwick tensile tester found in Er-Bakır Electrolytic Copper Products Inc. using 250-mm-long rods.

Current measurement tests to determine the conductivity properties of the wires used in the study were carried out in Buster Resistomat 2304 resistance measurement device found in Er-Bakır Electrolytic Copper Products Inc. using 1000-mm-long wires at constant temperature.

Resistance measurement results were recorded, and the conductivity values of the samples were determined by the relation given in Equation 2.1

$$1/\rho = (RxL)/S \quad (2.1)$$

In this relation, R: Resistance value measured from the device (ohm), S: Sectional area of the rod (mm²), L: Rod length (mm), 1/ρ: Conductivity value (ohm.mm/mm²).

To determine the relationship between mechanical properties and product quality, metallographic studies were carried out at Er-Bakır Electrolytic Copper Products Inc. using a 1000X-magnification metallurgy microscope. Accordingly, the standard metallographic sample preparation method was adopted. Sanding process was carried out using 200-320-400-600-800-1200 mesh sandpapers, respectively. In the final polishing process, 1-µm 1/6 Alumina solution was used with Nap felt. The samples were etched with an etching solution consisting of 25 mL NH_3 (ammonia), 1.5 mL H_2O_2 (hydrogen peroxide) and 25 mL distilled water.

3. Results and Discussions

Oxygen content had significant effects on mechanical properties, cold shaping behavior and wire drawing capability [23-27]. Figure 1 shows the effect of oxygen content on tensile strength for ETP rods, OFC rods and rods with three different alloys (CuSn0,18, CuMg0,5, CuAg0,10) with comparison.

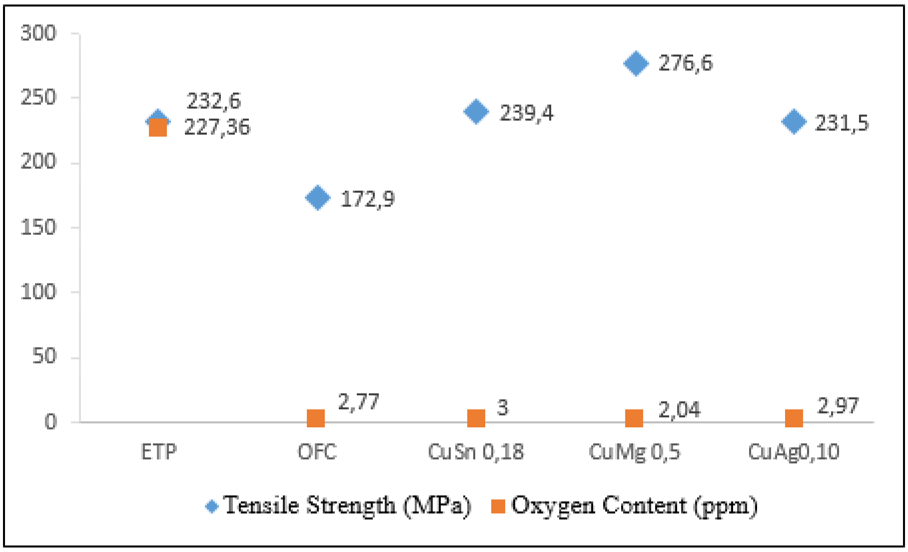

Figure 1. The Effect of Oxygen Content on Tensile Strength

As seen in Figure 1, the tensile strength of the ETP copper with 227 ppm of oxygen was 232 MPa, while the tensile strength of the OFC with approximately 2.8 ppm oxygen content was 172 MPa. In alloyed samples, although the content of oxygen was low, it was observed that the tensile strength increased up to 276 MPa due to the effect of alloy element. Based on these results, it can be said that, in accordance with the literature, the oxygen content caused a slight increase in tensile strength (Opie et al., 1973; Ayhan, 2002; Smets&Morties, 1983). The factors that cause this increase are that the mechanism of deformation hardening of ETP occurs more rapidly, especially at low stress values (Smets&Morties, 1983), and that the impurities combine with oxygen to form oxide inclusions in the microstructure (Ayhan, 2002; Smets&Morties, 1983).

The effect of oxygen content on tensile strength for ETP rods, OFC rods and copper rods with three different alloys (CuSn0.18, CuMg0.5, CuAg0.10) are given in Figure 2 in comparison.

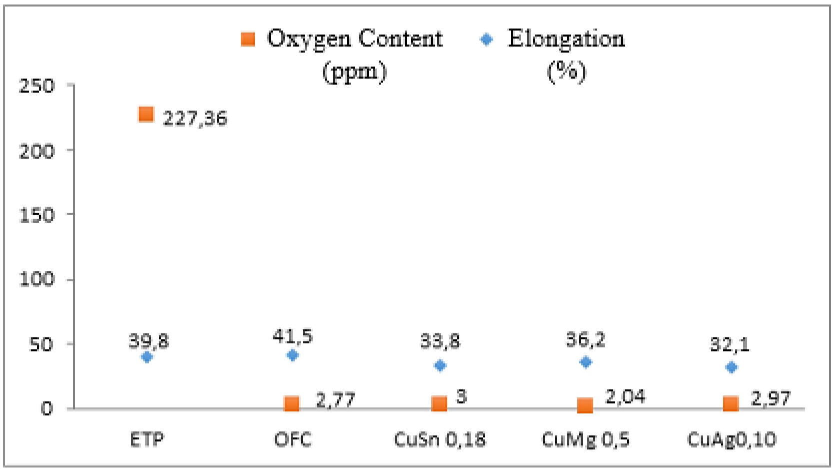

Figure 2. The Effect of Oxygen Content on Elongation

As seen in Figure. 2, the elongation of the ETP copper with 227 ppm of oxygen was 40%, while the elongation of the OFC copper with oxygen content of approximately 2.8 ppm, with a slight increase, was 41.5%. In alloyed samples, it was observed that the elongation was in the range of 32-36% due to the effect of alloy element, indicating an increase in ductility. In the literature, this result was associated with the embrittlement of the resultant material by forming stress concentration centers in copper oxide particles found in the ETP copper, causing a higher void stress concentration center in the breakage zone (Ivanich&Kochowski, 1993; Opie et al., 1970; Opie et al., 1973; Ayhan, 2002; Kayalı et al., 1990). In addition, the proportions of the inclusions in the wire drawing process do not change, in other words, the inclusions are not deformed. Therefore, breakages in inclusions and accordingly increases in the density of inclusions take place in a certain area of the rod (Arıkan et. al, 1994). Thus, it can be said that oxygen-free copper (OFC) absorbs a high amount of energy before breakage and can be further deformed.
Within the scope of the study, the effect of oxygen content on the wire drawing capability of the rod was studied for three months for electrolytic tough pitch (ETP) and oxygen free copper (OFC) wire rods and alloyed copper wire rods. In this context, the quality of the wires in the range of 0.050-0.675 mm diameter was tested with six parameters in the production line and the number of breakages were determined for three months. In Figure 3, the number of breakages for ETP, OFC and alloyed copper rods are compared according to six basic breakage parameters. Since the number of breakages in rod with three different alloys were very close, the average values are given in the Figure.

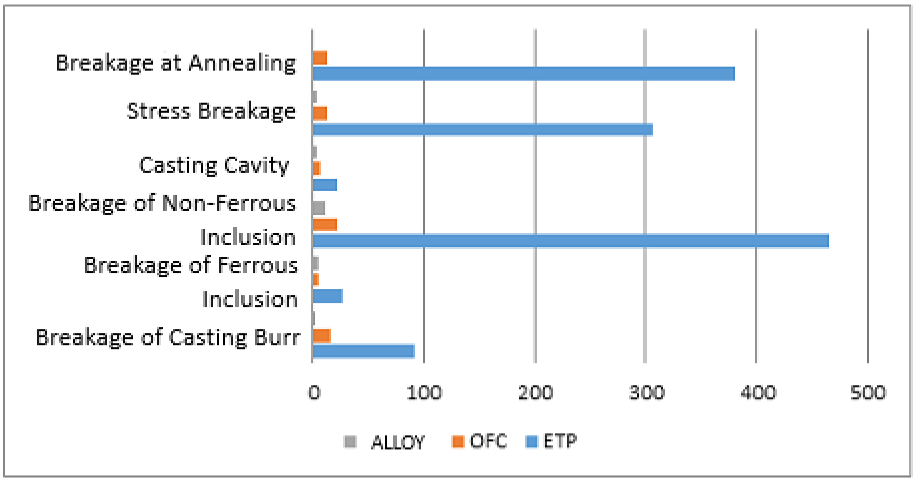

Figure 3. The Effect of Oxygen Content On Wire Drawing Capability

As seen in Figure 3, the number of breakages in ETP copper rods during the same period was considerably higher than both OFC and alloyed copper rods. It was found that the oxygen content had a significant effect on the wire drawing capability of wires, and the wire drawing capability performance of OFC rods and alloyed rods were substantially higher than those of ETP copper rods. In the literature, the effect of the oxygen content on wire drawing capability was also associated with mechanical properties including tensile strength and elongation (Smets&Morties, 1983; Ivanich&Kochowski, 1993; Arıkan et al., 1994; Opie et al., 1970; Opie et al., 1973; Ayhan, 2002; Smets&Morties, 1983; Yeang, 1982; Kayalı et al., 1990). In wire drawing process, high tensions occur during cold deformation especially in smaller diameters and deformation hardening is seen in the material. Therefore, annealing temperature and durations are very important in reducing the hardening and the wire drawing capability. Another important factor affecting the wire capability is the formation of insoluble oxide inclusions by the compound formation of impurities with oxygen. These oxide inclusions cause excessive deformation hardening during deformation and form brittle breakage initiation points by the notch effect. Therefore, in the electrolytic refining process, the content and the quantity of the impurities exceed the determined limits, adversely affecting the quality of the product (Suzuki&Kanno, 1985; Meshal, 1982; Tanaka&Yoshida, 1979; Bowyer, 1999; Prasad&Rao, 2004; Jakani et al., 2007).

The effect of oxygen content on the conductivity of the wire is given in Figure 4 for ETP and OFC copper rods and copper rods with three different alloys (CuSn0.18, CuMg0.5, CuAg0.10). As seen in Figure 4, the conductivity value was not significantly affected by the oxygen content. It is thought that the fluctuations in the conductivity values of alloyed copper wire rods were affected from the cathode input quality and cathode impurity values (Knych et al., 2011; Knych et al., 2010; Smart, 1987; Knych et al., 2011; Kynch et al., 2009; Kynch et al., 2011).

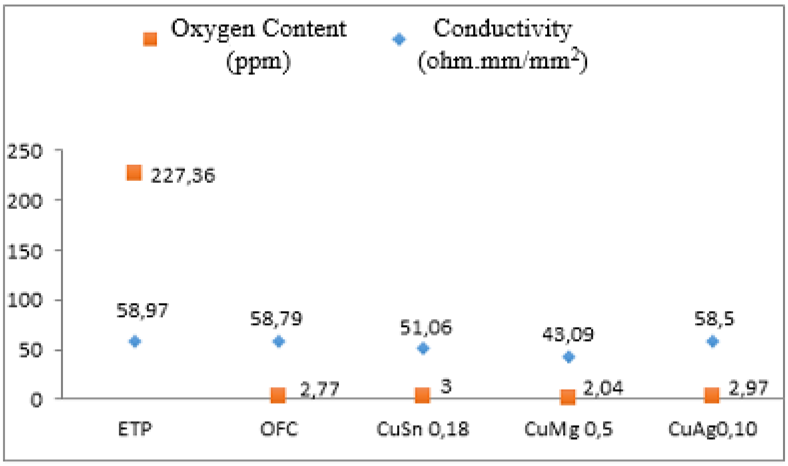

Figure 4. The Effect of Oxygen Content on Wire Conductivity

Optical microscope images of the metallographic studies performed to determine the relationship of the oxygen content with the change in tensile strength test results and the microstructure are shown in Figure 5. As seen in Figure 5, the ETP copper particle structure had a coarser and irregular structure than that of the OFC. In addition, due to the increased oxygen concentration in ETP copper, there were heterogeneously dispersed oxide inclusions in the structure. Unlike OFC copper, there were twinnings in these regions where oxide particles were present. Also, thinning was observed in particle size per unit area. It was thought that stresses formed during the deformation of the oxide inclusions, which were harder than the main matrix, serve as a core in the formation of new particles and make the microstructure fine-grained (Ayhan, 2002; Adams et al., 1997). It was also thought that one of the main reasons for the excessive breakages occurred in ETP copper in the wire drawing process was the presence of these oxide inclusions. It was seen that the presence of inclusions in the alloyed copper microstructure, which had a very low oxygen content in terms of ppm, was considerably less than that in the ETP copper and the particle structure was more homogeneous.

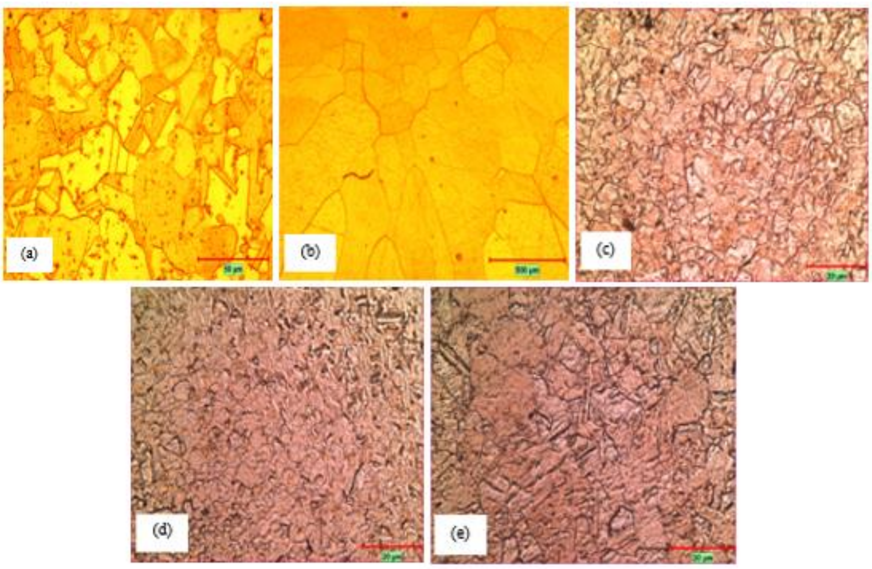

Figure 5. Typical Microstructures (a) ETP, (b) OFC, (c) CuSn0.18 (d) CuMg0.5 (e) CuAg0.1

4. Conclusions

Examination of the effect of oxygen content on the mechanical and conductivity properties and the product quality of the copper wires produced by Contirod and Up-Cast continuous casting methods yielded the following findings:

- It was determined that the oxygen content caused an increase in tensile strength and a decrease in elongation. It was thought that the fact that the impurities which were found in trace amounts in the microstructure bound with oxygen and formed oxide inclusions harder than the main matrix had led to an increase in tensile strength. Also, the fact that copper oxide particles formed stress density centers and embrittled the material by forming higher void concentration in the breakage zone had led to a decrease in elongation.
- It was found that the oxygen content had a significant effect on the wire drawing capability and that the wire drawing capabilities of OFC and alloyed copper rods were substantially higher than those of ETP copper rods. The number of breakages in ETP copper rods during the same period was considerably higher than both OFC and alloyed copper rods. In wire drawing process, high tensions occurred during cold deformation especially in smaller diameters and deformation hardening was seen in the material. It was thought that impurities formed oxide inclusions by binding with oxygen and these oxide inclusions caused excessive deformation hardening during deformation and formed brittle fracture initiation points by the notch effect, leading to a decrease in wire drawing capability performance.
- It was seen that the conductivity value of the rods was not significantly affected by the oxygen content, and also the conductivity values fluctuated due to the effect of the cathode input quality and the impurities.
- As a result of the microstructure analyses, it was observed that the ETP copper particle structure had a coarser and irregular structure compared to that of the OFC. In addition, it was seen that there were heterogeneously dispersed oxide inclusions in the structure due to the increased oxygen concentrations in ETP copper, and unlike OFC, twinnings formed in these regions where oxide particles were found, and also thinning was determined in the particle size in unit area. It was thought that oxide inclusions, which were harder than the main matrix, acted as the core in the formation of new particles with the tension formed during deformation and made the microstructure finely grained. It was seen that the presence of inclusions in the alloyed copper microstructure, which had a very low oxygen content in terms of ppm, was considerably less than that in the ETP and the particle structure was more homogeneous.

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