

Original Research Article

<http://dx.doi.org/10.20546/ijcmas.2017.602.033>

## Monitoring the Effect of Additive Agents and Other Parameters on Copper Deposition by Electro Refining Process

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### ABSTRACT

#### Keywords

Copper electrorefining process, Additive agents, Purity, Deposition rate, Morphology, Electrolyte residence time, Current efficiency, Power consumption.

#### Article Info

##### Accepted:

12 January 2017

##### Available Online:

10 February 2017

Deposition of copper by electrorefining process was attained to observe the effect of the additive agents on process performance (cathode purity, surface morphology, deposition rate, current efficiency and power consumption). The deposition was done in acidic media with 40 g/l and 160 g/l concentration of cupric ions and sulfuric acid, respectively. The operating parameters were utilized: electrolyte residence time 6, 4 and 2 h, electrodes spacing 15, 30 and 45 mm, with and without addition of additive agents 3, 2.4 and 40 (mg/l) of the animal gelatin, thiourea and chlorine ions respectively, current density 300 A/m<sup>2</sup> and electrolyte temperature 35, 50 and 65°C. To clear up the produced copper properties XRF, SEM and EDX analyses were carried out.

### Introduction

A metal demand is growing beside the worldwide inhabitation increases and metals are utilized in a larger range of industries, especially connected with the spread of novel technologies. Metals are absolutely necessary to reinforce economic development and the work of modern civilization (Lusty *et al.*, 2015).

Copper acting a considerable role in the manufacturing production because it is simple to work with, effective electricity and heat conductivity and it has a good corrosion

resistance Copper market is one of the biggest of all metals backwards iron and aluminum (Eugie *et al.*, 2015). Pyro metallurgical process was achieved 80% of global copper production (Boulamanti *et al.*, 2016).

In the electro refining cell the casting anodes were dissolved in the electrolyte solution and the electrical current was applied to deposit the copper as a pure metal on the cathode (Ghodrat *et al.*, 2016). Additional benefit was gained from process by recovery of cell slimes to produce valuable metals like selenium, gold, tellurium and silver.

Comparatively impure casting anodes are hanging in an acidic electrolyte every other among thin pure copper starter sheets which will come to be the cathodes. On applied copper electrorefining processes, acidic electrolyte is used exclusively, the usage of acidic electrolyte for the reason that power and chemicals costs are low and on account of the control of these solutions are simple and forward straight (John *et al.*, 2002; Schlesinger *et al.*, 2010).

Anode must be connecting to the positive pole of the electrical supply, whereas the pure copper starter sheet must be connecting to the negative pole of the electrical supply. When the electrical supply is turn on, the atoms of copper will lose electrons and diffused to the cathode through the electrolyte, then it will deposit as pure copper, for every ion deposited onto the cathode, else ion passes in the electrolyte from the anode. Finally the anode is spent and its impurities either stay dissolved in the electrolyte or drops to the bottom of the cell creating the slime, by this process pure copper cathode is yield and other expensive metals existing in the anode like platinum, silver, gold, or palladium, can be recovered from the slime.

The constantly enormous demand leads to improve the copper electrorefining process, the improvement was employed by modified the design of the electrorefining cell, the electrolyte movement control at the electrodes surface, optimized the quantities of the additive reagents and advanced of substitute additives. Also in the last years the current density was raised to high values in order to raise the production rate, with keeping of copper purity level (Stelter *et al.*, 2004). Different types of additives organic (and/or) inorganic are widely used in copper electrorefining processes due to their abilities to prevent the formation of dendrites and nodules, these abilities lead to improve copper

deposit characteristics such as purity and surface morphology (Safizadeh *et al.*, 2011). The electrolyte heating is costly but its valuable influence in copper electrorefining process (Mark *et al.*, 2011). Electrodes spacing play an important role in the copper electrorefining process, so it has to be set to improve the specifications of produced cathodes (Ntengwe *et al.*, 2010). The rate of circulation must realize a minimal change of cell electrolyte every 4-6 h. A steady slow electrolyte movement in the cell is needful for increase the mass transport, settle down of anode slimes at the cell bottom, make a good control to electrolyte temperature and carry off the dissolving contaminations from the cell (Ntengwe, 2008).

The main objectives of present work are: design, construct and install of a laboratory electro refining cell, study the effect of the additive agents on cathode purity, surface morphology, deposition rate, current efficiency and power consumption, also optimizing the operational parameters of process by obtain the optimum operating conditions that provide the finest quality and quantity of the produced copper.

## **Materials and Methods**

### **Theory**

The fundamentals of electrorefining process based on electrochemical kinetics philosophies (Derek *et al.*, 1993). Like every electrodeposition processes, the electrodeposition of copper is an electrolytic process that is created from electrochemical reduction reaction on cathode, so the reducing copper produce is deposited on the cathode surface. If other (undesired) reactions are does not happening in the same time, at that point it can assume that the reaction at cathode in the electrolyte solution is only the desired copper reduction.



The copper electrodeposition process contains many steps. Principally the steps are movements of reactive ions from electrolyte to the surface of cathode, adsorption of the ions, transfer of the charge at the cathode surface, cathode surface diffusion and metal deposition, nucleation occurs first and then developing into crystal structure (Fischer, 1954; Lee, 2006).

In general organic additives have the ability for covering the electrode surfaces with a layer formed from other component and chloride ions, additives considerably affect the relationship between current and potential of process, thus the carefully chosen of additives must be employ agreeing to their role at interface film between the electrolyte and the electrodes to take control the nucleation rate and growth rang during the copper electrorefining process.

The theoretical deposit cathode weight  $W_{\text{theo}}$  can be calculated from Eq.(2) by Faraday's law;

$$W_{\text{theo}}(\text{g}) = \frac{I \cdot t \cdot A_w}{Z \cdot F} \dots (2)$$

where I is the applied current, t is deposition time,  $A_w$  is copper atomic weight, Z is electron valency and F is Faraday's constant.

The actual cathode deposition rate ACDR can be calculated from Eq. (3) by divided the actual deposit weight of cathode over the deposition time and the deposition area (Aromaa, 2007).

$$\text{ACDR} (\text{g/h.m}^2) = \frac{W_{\text{acut}}}{t \cdot A} \dots (3)$$

The current efficiency CE% represented the proportion of current transient over an electrolytic cell in order to achieve the wanted electrochemical reaction. It can be calculated from Eq. (4):

$$\text{CE} (\%) = \frac{W_{\text{acut}}}{W_{\text{theo}}} \cdot 100 \dots (4)$$

However, there is a continuous need to minimizing power consumption by reducing cell voltage, by increasing current efficiency and keeping good electrical connections during the electrorefining process (Kruyswijk, 2009). The power consumption can be calculated from Eq. (5):

$$P (\text{kW.h/kg}) = \frac{V_{\text{cell}} \cdot I \cdot t}{W_{\text{acut}}} \dots (5)$$

Where  $V_{\text{cell}}$  is the cell voltage.

### **Experimental work**

Three parts consist of 24 experiment were achieved. Electrolyte was prepared by using annular sulfuric acid supplied by BAKER company with specific gravity 1.84 and purity 97%, diluted with distilled water to obtain an electrolyte solution of 160 g/l, then 160 g of copper sulfate pentahydrate supplied by Shanghai Mintchem Company with purity 98%, added to one liter of this electrolyte solution and stirred to gain 40 g/l of cupric ions concentration.

Figure 1 represents the experimental apparatus were utilized in the present work. A rectangle lab scale cell constructed from Pyrex glass with active volume of 720 ml was used. The starting cathode sheet was made of pure copper with total area of (100\*80\*mm) and immersed area of (70\*70 mm) with thickness 0.6 mm. Anode was used with a copper content of (98.48 % wt. Cu) and with total area of (100\*80\*mm) and immersed area of (75\*80 mm) with thickness 6.5 mm. Before every single experiment, three steps were done for electrodes preparation, the first step was polishing with (220, 320 and 800) grades of sandpaper in order to eliminate film oxides & any contaminations on the surface, in the second step ethanol was used to remove any

grease, in the third step electrodes were immersed in (1/5) volume ratio of sulphuric acid to distilled water mixture, after finishing of each steps the electrodes were washed by distilled water and dried by gauze. The electrodes saved inside the desiccator overnight before utilized. The electrical circuit contains a digital DC power supply connected with the cell and ammeter in series, while the voltmeter connected in parallel with the cathode and the anode respectively and the current density was  $300 \text{ A/m}^2$ .

Part one with stationary electrolyte and without adding of additive agents, experimental program was to study the effect of electrodes spacing (S) 15,30 and 45 mm, and electrolyte temperature (T) 35,50 and  $65^\circ\text{C}$ , on process performance (cathodepurity, surface morphology, deposition rate, current efficiency and power consumption).

Part two with stationary electrolyte and with adding of additive agents 3, 2.4 and 40 (mg/l) of the animal gelatin, thiourea and chlorine ions respectively, experimental program was to study the effect of electrodes spacing (S) 15,30 and 45 mm, and electrolyte temperature (T) 35,50 and  $65^\circ\text{C}$ , on process performance items.

While the third part deals with circulated electrolyte and with adding of additive agents 3, 2.4 and 40 (mg/l) of the animal gelatin, thiourea and chlorine ions respectively, to study the effect of electrolyte residence time ERT 6, 4 and 2 h, and electrodes spacing (S) 15 and 30, with constant current density (CD)  $300 \text{ A/m}^2$  and electrolyte temperature (T)  $65^\circ\text{C}$  on process performance items.

## **Results and Discussion**

### **Part One**

Table 4 shows the actual cathode deposition rate (ACDR), current efficiency (CE%) and

power consumption(P) values resulted from this part.

### **Effect of the electrolyte temperature**

As electrolyte temperature increases cathode purity will increase. It can be clarified that increase of electrolyte temperature leads to decrease its density and viscosity, this impact make the bigger contamination particles have a greater settling velocity and will be precipitate to the cell bottom more quickly, so be less probability to deposited on the cathode surface, while the finer contamination particles have a lesser settling velocity will be suspended in the electrolyte, so be more probability to deposited on the cathode surface.

When electrolyte temperature decreases cathode surface morphology declined and become rougher. The possible explanation that decrease electrolyte temperature will decrease the electrical conductivity of electrolyte and that will hinder the current density distribution in the cell causing unequal spreading of deposit grains over cathode surface producing a rougher deposit.

When the electrolyte temperature increase current efficiency will increase, it can be referred to Arrhenius equation which states that increasing of electrolyte temperature leads to increase the reaction rate of copper deposition; therefore the current efficiency will increase.

The increasing of the electrolyte temperature caused reduction in the power consumption, the increasing of the electrolyte temperature gives rise to minimize polarization of cathode and anode and increase the electrolyte conductivity.

Decrease electrolyte temperature decreases ACDRA as shown in figure 2. It can be interpreting that the diffusion coefficient of

the cupric ions will decrease with decreasing of the electrolyte temperature, so hindering mass transportation that is in a good agreement with Ibrahim (2016) (Table 1).

### **Effect of the electrodes spacing**

As the electrodes spacing decrease the cathode purity increased very slightly, the possible explanation that the variation in electrodes spacing does not have a significant influence on the natural convection which affect the impurities motion during the process.

When electrodes spacing increase cathode surface morphology become rougher, it can be interpreting that the electrolyte resistivity increase with increasing of the electrodes spacing and that will causing a bad current density distribution through the cell producing unsatisfactory distribution of the deposit grains on the surface creating a rougher deposit form.

It can be observed easily that increase electrodes spacing decrease ACDR, it can be explained that increase electrodes spacing would increase the electrolyte resistivity and that would reduce the electrical field intensity which drive the charging species to deposit on the cathode surface.

A negative influence of the electrodes spacing increasing on current efficiency, the probable explanation that the unwanted reactions rates may be maximized.

Increase electrodes spacing would increase power consumption as shown in figure 3, it can be explained that electrodes spacing increasing would increase the electrolyte resistivity and that can be maximized the cell voltage due to highly hindering to electrical current passing through the electrolyte.

The optimum operating parameters were obtained in Exp. No. 7, the current density  $300 \text{ A/m}^2$ , the electrolyte temperature  $65^\circ\text{C}$  and the electrodes spacing 15 mm. These operating parameters are producing a copper with maximum purity as shown in Appendix A (98.70 % wt.Cu), semi smooth deposit surface, supreme ACDR  $348.0 \text{ (g / h.m}^2\text{)}$ , maximum CE (97.84 %) and minimum P  $0.6174 \text{ (kW.h/kg)}$ .

### **Part two**

Table 5 shows the actual cathode deposition rate (ACDR), current efficiency (CE%) and power consumption (P) values resulted from this part (Table 2).

### **Effect of electrolyte temperature**

Decrease electrolyte temperature would decrease the cathode purity, it can be explain that decrease electrolyte temperature leads to increase its density and viscosity, this influence inhibits the precipitation of contamination particles to the cell bottom, hence are more probability to deposit of the contaminations on the cathode surface.

It can be seen from figure (4) that when the electrolyte temperature decrease the current efficiency will decrease, the possible explanation according to Arrhenius equation which states that the decreasing of electrolyte temperature leads to decrease the reaction rate of copper deposition, therefore the current efficiency will decrease.

When the electrolyte temperature increase the cathode surface morphology improved and become finer as shown in figure 5, it can be clarified that the increase of electrolyte temperature would increase the electrical conductivity of the electrolyte and that will ease the distribution of current density in the cell causing equal spreading of the deposit



grains over the cathode surface producing a finer deposit.

Decreasing of the electrolyte temperature would maximize the power consumption due to decrease the electrolyte conductivity and gives rise to polarization of cathode and anode and cell voltage. By comparison between experiments number in part one and experiments number in part two, the addition of additive agents will increase power consumption from 0.6174 to 0.8568 kW.h/kg.

The increasing of the electrolyte temperature would raise the deposition weight and deposition rate, it can be interpreting that the electrolyte density will decrease with increasing of the electrolyte temperature, thus ease the mass transportation.

### **Effect of electrodes spacing**

Increase the electrodes spacing would decrease the cathode purity somewhat, it can be clarified that the alteration in electrodes spacing have not an important impact on the natural convection which affect the impurities motion during the process.

A positive influence of the electrodes spacing decreasing on the cathode surface morphology and become finer as shown in figure 5, the possible explanation that the electrolyte resistivity decrease with decreasing of the electrodes spacing, and that would creating a best current density distribution through the cell producing satisfactory distribution of the deposit grains on the surface creating a finer deposit form.

It can be notes that when the electrodes spacing increasing the current efficiency would decrease, it can be clarified that the rates of undesirable reactions were maximized, and that is in a good agreement with Ntengwe (2008).

When the electrodes spacing decrease the power consumption would decrease, the probable analysis that decreasing electrodes spacing would decrease the electrolyte resistivity and that can be minimized the cell voltage due to easily passing of the current through the electrolyte.

As the electrodes spacing decrease the deposition weight and deposition rate would increase somewhat as shown in figure 6, it can be interpreting that decrease the electrodes spacing would decrease the electrolyte resistivity and that would enhance the electrical field intensity which was drive the charging dissolution species to deposit on the cathode surface. The deposition rate of experiment number 17 (342.2 g / h.m<sup>2</sup>) was less than of experiment number 8 (347.4 g / h.m<sup>2</sup>), that is mean the addition of additive agents will reduce the deposition rate.

The optimum operating parameters were obtained in Exp. No. 16, the current density 300 A/m<sup>2</sup>, the electrolyte temperature 65 °C and the electrodes spacing 15 mm. These operating parameters are producing a copper with maximum purity as shown in Appendix A (99.79 % wt.Cu), smooth deposit surface, higher ACDR 344.0 (g / h.m<sup>2</sup>), supreme CE (96.72 %) and minimum P 0.8568(kW.h/kg).

### **Part three**

Table 5 shows the actual cathode deposition rate (ACDR), current efficiency (CE%) and power consumption (P) values resulted from this part (Table 3).

From the optimum operating conditions of parts one and two, it decided to fixed the electrolyte temperature with 65 °C and the electrodes spacing with 15 mm, also and based on logical expectation that the electrolyte circulation with short electrodes spacing 15 mm can deteriorate the cathode

purity due to high forced convection of charged contaminations species that may deposit on cathode surface, also short electrodes spacing can increased the chances of short circuit and reduced the current efficiency, hence another electrodes spacing of 30 mm was employed because it gave an acceptable results in part one and two.

### **Effect of the Electrolyte Residence Time (ERT)**

In comparison, the electrolyte circulation slightly increased mass transport than stationary conditions, for the same operating parameters ACDR increase from 344.0 in Exp. No. 16 to 349.0 g / h.m<sup>2</sup> in Exp. No. 21. Also when ERT decrease the ACDR would increase, the feasible analysis that decreasing ERT would increase the forced convection, and that would decrease copper ions near the anode and increases the copper ions near cathode, subsequently the natural convection from anode to cathode would increase and makes a quicker moving of copper ions.

Surface morphology in case of electrolyte circulation is better than electrolyte stationary situations. In addition, as the ERT decrease the cathode surface morphology becomes slightly finer as shown in figure 7, it can be clear up that ERT decreases would increase the forced convection and that would decrease the Nernst diffusion layer thickness and permits to produce a smooth copper deposition.

In general, electrolyte circulation increase cathode purity compared with stationary electrolyte state, for the same operating parameters purity was increased from 99.75% in Exp. No. 17 to 99.91% in Exp. No. 22 as shown in Appendix (A). Besides that in electrolyte circulation state, decrease ERT more than 4 hours leads to decrease cathode purity, it can be interpreting that the density gradient make an electrolyte loop between the

cathode and the anode (natural convection), the electrolyte close the anode is denser than that in facade of the cathode, because the anode is the source of cupric ions by dissolution operation, while it is deposited on the cathode surface, the electrolyte loop is moving with a downward trend over the anode surface and an upward trend over the cathode surface. When the electrolyte is circulate, a flow pattern with a trend from the bottom to the top will be created, hence the upward electrolyte current close the cathode will be strengthened, upward flow has important influence on contaminations particle conduct, so more probability with lesser ERT to contaminations deposited on cathode surface and deteriorate the purity. As a rule, electrolyte circulation minimizes the power consumption, for the same operating parameters P decrease from 1.0289 in Exp. No. 17 to 0.8418 (kW.h/kg) in Exp. No. 24. Decrease ERT would decrease power consumption, the possible explanation that the decreasing of ERT would increase the forced convection which enhanced the removing of slimes adhered on anode surface and that would permits to easily passing of current and reduces the cell voltage beside the minimization of electrodes polarization.

Compare with stationary state, the circulation of electrolyte increase the current efficiency, for the same operating parameters CE% increase from 96.72% in Exp. No. 16 to 98.14% in Exp. No. 21. Furthermore, It can be observed from figure 8 that increasing of ERT would decrease the current efficiency, it can be make clear that increase ERT would decrease the forced convection and that would slows down the speed of copper ions from anode to cathode leads to minimize the reaction rate of copper deposition, therefore the current efficiency will decrease.

### **Effect of electrodes spacing**

When the electrodes spacing increase from 15

to 30 mm the cathode purity would slightly increase, the possible explanation that with electrolyte circulation, the short electrodes spacing may deteriorate cathode purity due to high forced convection of the charged contaminations species that may deposit on cathode surface.

It can be observed that increase of electrodes spacing would deteriorate the cathode surface morphology and become rougher as shown in figures 7, it can be clarified that the electrolyte resistivity increase with increasing of the electrodes spacing, and that would

generate a bad current density distribution through the cell producing unacceptable distribution of the deposit grains on the cathode surface creating a rougher deposit shape.

When the electrodes spacing increase the deposition rate would decrease slightly, it can be clarified that increase the electrodes spacing would increase the electrolyte resistivity and that would minimize the intensity of electrical field which drive the charging dissolution spices to deposit on the cathode surface.

**Table.1** Summary of the operating parameters for part one (stationary electrolyte without adding of additive agents)

Exp. No.	CD A/m <sup>2</sup>	T °C	S mm
1	300	35	15
2	300	35	30
3	300	35	45
4	300	50	15
5	300	50	30
6	300	50	45
7	300	65	15
8	300	65	30
9	300	65	45

**Table.2** Summary of the operating parameters for part two (stationary electrolyte with adding of additive agents)

Exp. No.	CD A/m <sup>2</sup>	T °C	S mm
10	300	35	15
11	300	35	30
12	300	35	45
13	300	50	15
14	300	50	30
15	300	50	45
16	300	65	15
17	300	65	30
18	300	65	45



**Table.3** Summary of the operating parameters for part three (circulated electrolyte with adding of additive agents)

Exp. No.	CD A/m <sup>2</sup>	T °C	S mm	ERT h
19	300	65	15	6
20	300	65	15	4
21	300	65	15	2
22	300	65	30	6
23	300	65	30	4
24	300	65	30	2

**Table.4** ACDR, CE% and P of part one

Exp. No.	ACDR g / h.m2	CE %	P kW.h/kg
1	346.1	97.30	0.8944
2	345.1	97.03	0.9814
3	344.1	96.74	1.1377
4	346.7	97.49	0.7340
5	346.1	97.32	0.8576
6	345.5	97.15	1.0227
7	348.0	97.84	0.6174
8	347.4	97.68	0.8073
9	346.2	97.33	0.9639

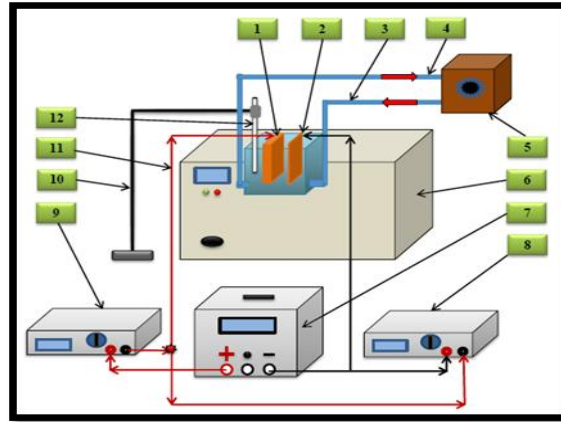
**Table.5** ACDR, CE% and P of part two

Exp. No.	ACDR g / h.m2	CE %	P kW.h/kg
10	336.4	94.58	0.9992
11	335.6	94.37	1.2387
12	334.7	94.11	1.3320
13	339.3	95.41	0.9469
14	338.1	95.05	1.1085
15	336.5	94.61	1.2466
16	344.0	96.72	0.8568
17	342.2	96.21	1.0289
18	340.0	95.60	1.1654

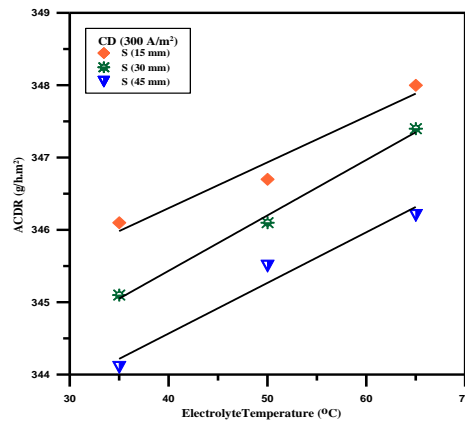
**Table.6** ACDR, CE% and P of part three

Exp. No.	ACDR g / h.m2	CE %	P kW.h/kg
19	345.3	97.09	0.7856
20	346.6	97.46	0.7101
21	349.0	98.14	0.6683
22	344.0	96.73	0.9510
23	345.4	97.11	0.8633
24	347.7	97.75	0.8418

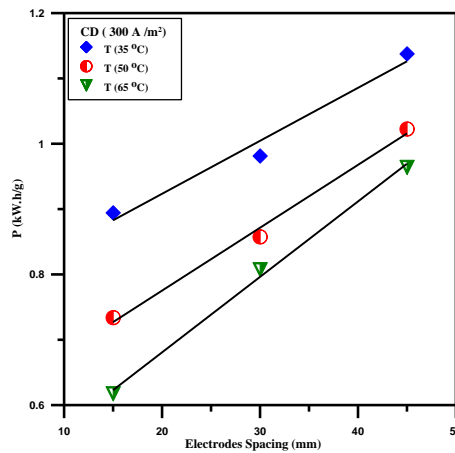
**Fig.1** Schematic diagram of experimental apparatus: 1- Anode, 2- Cathode, 3- Electrolyte input line, 4- Electrolyte output line, 5- Dosing pump, 6- Water bath, 7- Power supply, 8- Voltmeter, 9- Ammeter, 10- Stand, 11- Electrical wires, 12- Thermometer



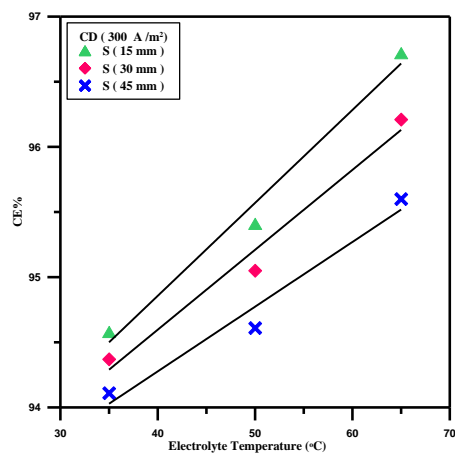
**Fig.2** Effect of electrolyte temperature on ACDR with constant CD 300 A/m<sup>2</sup> and S 15, 30 and 45 mm



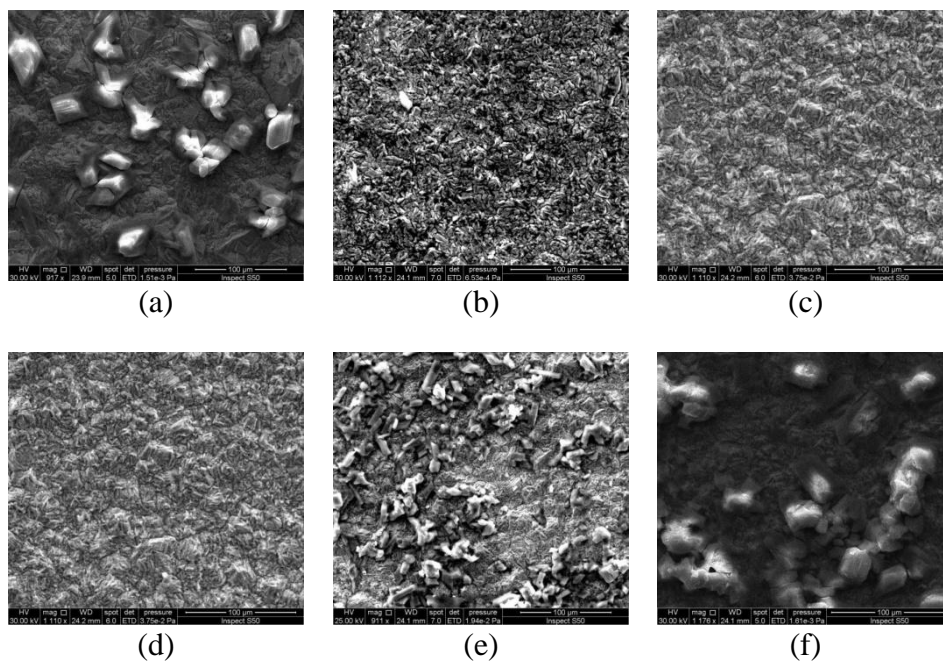
**Fig.3** Effect of electrodes spacing on P with constant CD 300 A/m<sup>2</sup> and T 35, 50 and 65 °C



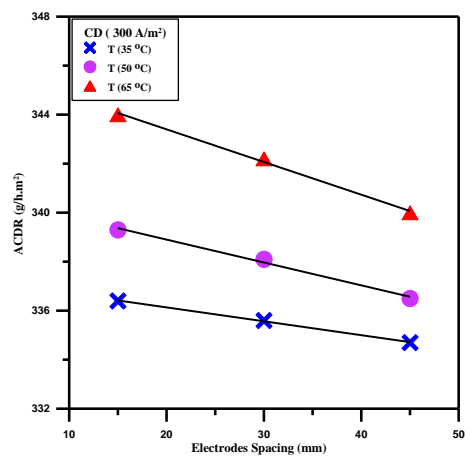
**Fig.4** Effect of electrolyte temperature on CE% with constant CD 300 A/m<sup>2</sup> and S15, 30 and 45 mm



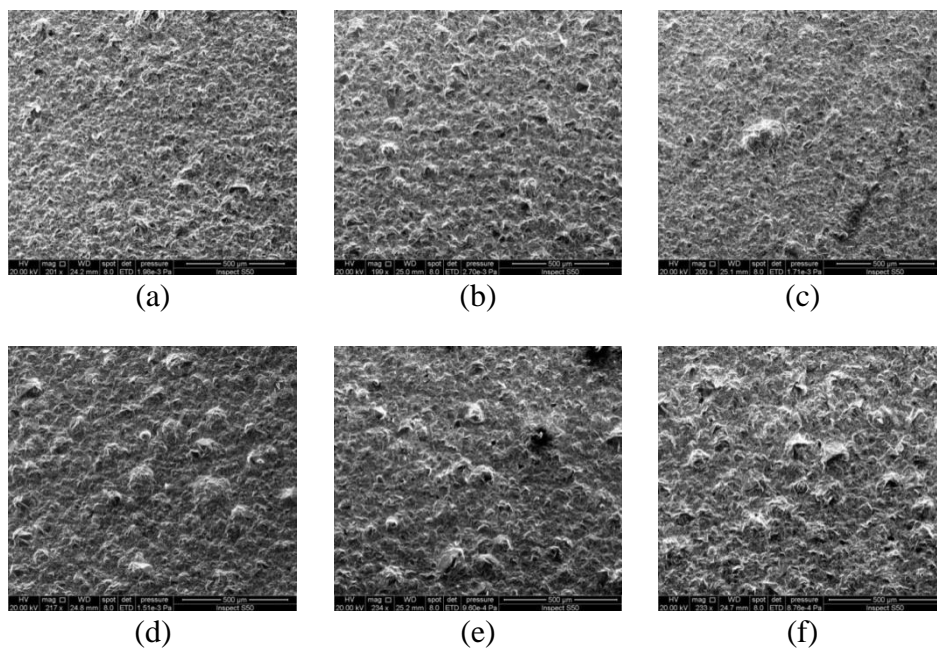
**Fig.5** SEM micrographs with CD 300 A/m<sup>2</sup> of part two, (a, b and c) effect of electrolyte temperature (35,50 and 65°C) respectively with S 15 mm, (d, e and f) effect of electrodes spacing (15,30 and 45 mm) respectively with 65°C



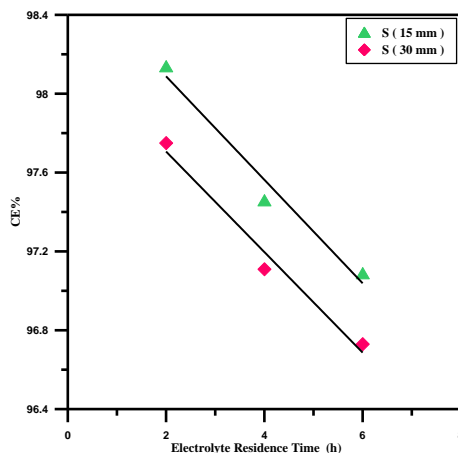
**Fig.6** Effect of electrodes spacing on ACDR with constant CD 300 A/m<sup>2</sup> and T 35, 50 and 65°C



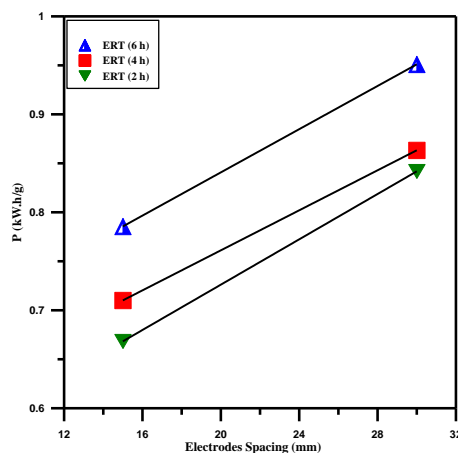
**Fig.7** SEM micrographs with CD 300 A/m<sup>2</sup> and T 65°C of part three, (a, b and c) S 15 mm and ERT 6, 4 and 2 h respectively, (d, e and f) S 30 mm and ERT 6, 4 and 2 h respectively



**Fig.8** Effect of ERT on CE% with T 65°C, S (15 and 30) mm and constant CD 300 A/m<sup>2</sup>

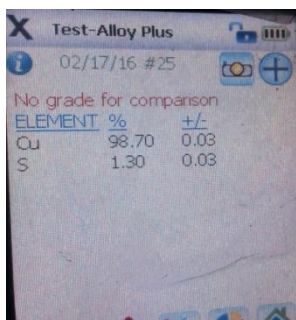


**Fig.9** Effect of Son P with T 65°C, ERT (2, 4 and 6) h and constant CD 300 A/m<sup>2</sup>

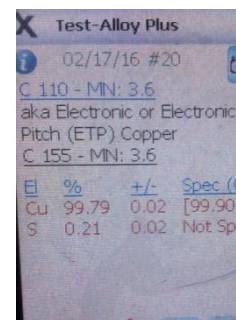
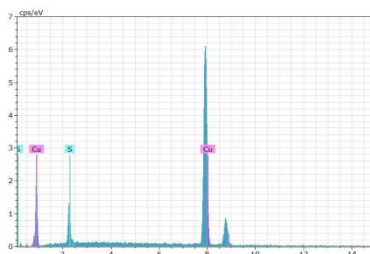


**Fig.10** XRF and EDX analyses for selected experiments

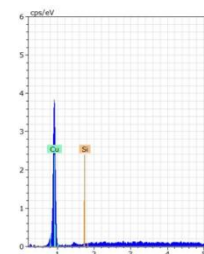
**XRF and EDX Analyses**



Exp.No. 7

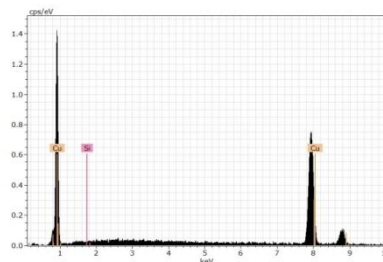


Exp.No.16





El	%	+/-	Spec (C 110)
Cu	99.91	0.03	[99.90-100]
Si	0.09	0.03	Tramp[0.45]



Exp.No. 22

Increase electrodes spacing would decrease the current efficiency, the probable analysis that the rates of unfavorable reactions may be maximized. As the electrodes spacing increase the power consumption would increase as shown in figure 9, it can be interpreting that the electrodes spacing increasing would decrease the electrolyte conductivity and that can be maximized the cell voltage due to greatly hindering to passing the current through the electrolyte.

In conclusion,

1. Generally, the addition of 3, 2.4 and 40 mg/l of animal gelatin, thio urea and chloride ions respectively with a current density 300 A/m<sup>2</sup> will improve cathode purity and morphology and done a slightly negative effects on ACDR, current efficiency and power consumption.
2. Increase electrolyte temperature will improve cathode purity and morphology, increase ACDR and current efficiency and minimize the power consumption.
3. Increase electrodes spacing in stationary electrolyte will slightly weaken cathode purity and morphology, faintly reduce ACDR and current efficiency and maximize the power consumption, while increase electrodes spacing with electrolyte circulation from 15 to 30 mm will slightly improve cathode purity only.

4. In general, electrolyte circulation improves cathode purity and morphology compared with stationary electrolyte state, furthermore decrease ERT will enhance cathode morphology, rise ACDR and current efficiency values and minimize power consumption, while ERT less than 4 hours leads to drop cathode purity.

### Nomenclature

- $A_w$  = Atomic weight, g/mol  
 $E^0$  = Standard electrode potential, V  
 $F$  = Faraday No. 96487, Columb/g equivalent  
 $I$  = Applied current, A  
 $P$  = power consumption, kWh/kg  
 $t$  = Deposition time, s  
 $V_{cell}$  = Cell voltage, V  
 $W_a$  = Actual deposit weight, g  
 $W_t$  = Theoretical deposit weight, g  
 $Z$  = Number of electrons transfer

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**How to cite this article:**

Hayder M. Abbas and Sarmad T. Najim. 2017. Monitoring the Effect of Additive Agents and other Parameters on Copper Deposition by Electro Refining Process. *Int.J.Curr.Microbiol.App.Sci*. 6(2): 270-284. doi: <http://dx.doi.org/10.20546/ijcmas.2017.602.033>