Proceedings of the International Conference on Mining, Material and Metallurgical Engineering
Prague, Czech Republic, August 11-12, 2014
Paper No. 113

Flotation of Nickel-Copper Sulphide Ore: Optimisation of Process Parameters Using Taguchi Method

Trust T. Masiya
University of Zimbabwe, Institute of Mining Research
P.O. Box MP167, Mount Pleasant, Harare, Zimbabwe
tmasiya@science.uz.ac.zw

Willie Nheta
University of Johannesburg, Department of Metallurgy
Faculty of Engineering & Built Environment,
South Africa, PO Box 526, Wits 2050, South Africa
wnheta@uj.ac.za

Abstract **-**Froth flotation is widely used for concentration of base metal sulphide minerals in complex ores. One of the major challenges faced by flotation of these ores is the ever varying grade and mineralogy. This therefore calls for a continual characterisation and optimisation of flotation parameters such that concentrator performance as a whole is always maintained. In this study, the robust Taguchi experimental design method was used to determine the optimum conditions for the flotation of nickel, copper and cobalt from a nickel-copper sulphide ore. The parameters investigated include collector dosage, percentage solids, depressant dosage and pH. The effects of these parameters at three different levels on the recovery of Ni, Cu and Co were investigated using an L_9 Taguchi orthogonal array. The optimum conditions for the recovery of the base metals are collector dosage, 80g/t; pH, 10.15; %solids, 25; and depressant dosage, 100g/t. Relative significance of flotation parameters (based on difference between max and min. values) indicates that pH has the most significant effect on the recovery of nickel, copper and cobalt during flotation. Analysis of variance showed that pH and depressant dosage were the most significant parameters affecting the recovery of Ni, while collector dosage and percentage solids were insignificant. None of the tested parameters significantly affected copper recovery whilst pH was found to also significantly affect cobalt recovery.

Keywords**:** flotation, process optimization, Taguchi orthogonal array, ANOVA.

1. Introduction

Froth flotation is widely used for separating base metal sulphide minerals in complex ores. One of the major challenges faced by the flotation of these ores is the ever varying grade and mineralogy as the ore is exploited (Kabuda et. al., 2011). As in any mineral processing operation the efficiency of the flotation separation is highly dependent on changes in feed characteristics all of which may influence product grade and recovery (Nashwa, 2007). There is therefore need to continually characterise such ores and optimise their flotation parameters such that concentrator performance as a whole is always maintained. Flotation efficiency depends on a number of parameters which include particle size, pulp density, water quality, pH and reagent dosage (Pérez-Garibay et. al., 2014; Muzenda, 2010; Saleh, et. al., 2008; Shuhua, 2006; Göktepe, 2002). Therefore, in order to achieve maximum recoveries and grades these parameters should be delicately balanced and optimised collectively (Muzenda et. al., 2011).

The Taguchi experimental design method has been shown to be an effective means for the improvement of quality and productivity in research and development (IIyas, 2010). It is a well-accepted technique that has been widely used for product design and process optimization in manufacturing and engineering worldwide [Kamaruddin et. al., 2004; Gopalsamy et. al., 2009; Rama and Padmanabhan, 2012; Sapakal and Telsang, 2012]. In recent years, its use has extended to include the metallurgical industry [Ilyas *et. al*., 2010; Haghi *et.al*. 2009; Temur *et. al*., 2009; Abali et al., 2006**]**. It provides a simplified systematic and efficient methodology for process optimisation (Bagchi, 1993). The greatest advantage of this method is the saving of effort in conducting experiments; saving experimental time, reducing the cost, and discovering significant factors quickly. The number of experiments that need to be done is greatly reduced compared to that required by other classical statistical methods such as factorial design.

The Taguchi method was therefore, selected to determine the optimum conditions for maximising the flotation recovery of Ni, Cu and Co from a nickel-copper sulphide ore. The effect on flotation performance of various parameters such as pH, collector dosage, % solids and depressant dosage at different levels was investigated. Therefore, the main objective of the study was to optimize the process parameters for the flotation of base metals from a nickel-copper sulphide ore.

2. Materials and Methods

2. 1. Materials

The nickel-copper sulphide ore used in this study was supplied by Trojan Nickel Mine located in Bindura, Zimbabwe. From the X-ray diffraction analysis, the main phases present in the ore were pentlandite (49.4%), pyrrhotite (41.2%) and quartz (4.6%), Fig.1. The ore which was supplied in lumpy form was subjected to crushing and grinding. The ore was ground to 70% passing 75 microns. Chemical analysis of this ore is shown in Table 1. 1% solutions of all flotation reagents i.e. collector (SIPX- sodium isopropyl xanthate) and depressant (Betamin 300) were used for the investigations and 10% solutions of both analytical grade sulphuric acid and sodium hydroxide were used as pH modifiers. For each test freshly prepared reagent solutions were used. Distilled water was used in all flotation experiments.

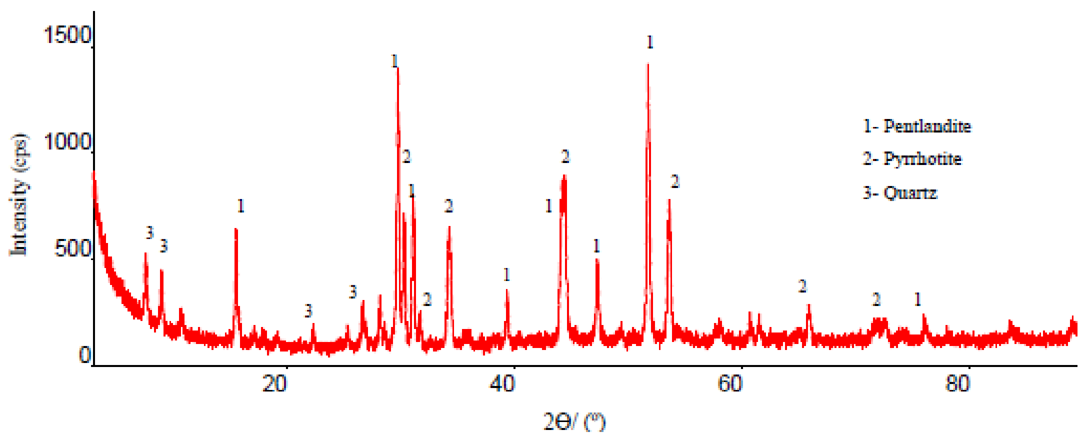

Fig.1. X-ray diffraction pattern of the nickel-copper sulphide ore sample

Table. 1. Chemical composition of the nickel-copper sulphide ore (mass fraction, %).

Component	**Ni**	**Cu**	**Co**	**Fe**	**MgO**	**SiO_2**	**SG**
%	12.61	0.71	0.17	47.04	0.13	10.60	4.38

2.2 Experimental Plan

Based on previous studies and literature, collector dosage, pH, percentage solids and the depressant dosage were chosen as the four main parameters to be investigated. According to the Taguchi design methodology, three levels were chosen for each parameter as illustrated in Table 2. Considering the four parameters and the relevant three levels, a Taguchi Orthogonal array (L_9) was established to execute the experiment. Nine experiments were therefore conducted as shown in Table 3. One (1) to three (3) levels appearing in Table 3 are the relative levels of the parameters indicated in Table 2. In this study interactions between parameters were not taken into consideration.

Table. 2. Experimental parameters and their relative levels.

Code	Parameter	Levels 1	2	3
A	pH	6.15	8.15	10.15
B	Collector Dosage (g/t)	40	60	80
C	Depressant dosage (g/t)	80	100	150
D	%Solids	20	25	30

Table. 3. Taguchi Orthogonal array ($L_9;3^4$) for influencing factors and their levels coded with actual values in brackets.

Experiment No.	pH	Collector Dosage (g/t)	%Solids	Depressant dosage (g/t)
1	1 (6.15)	1 (40)	1 (20)	1 (80)
2	1 (6.15)	2 (60)	2 (25)	2 (100)
3	1 (6.15)	3 (80)	3 (30)	3 (150)
4	2 (8.15)	1 (40)	2 (25)	3 (150)
5	2 (8.15)	2 (60)	3 (30)	1 (80)
6	2 (8.15)	3 (80)	1 (20)	2 (100)
7	3 (10.15)	1 (40)	3 (30)	2 (100)
8	3 (10.15)	2 (60)	1 (20)	3 (150)
9	3 (10.15)	3 (80)	2 (25)	1 (80)

In experiments based on the Taguchi design the use of signal-to-noise (SN) ratios is recommended for the optimisation of process parameters. In the Taguchi method the term signal represents the desirable value (mean) for the output characteristics and the term noise represents the undesirable values (standard deviation) for the output characteristic. The SN ratios can then be calculated based on the required response characteristics i.e. '*larger is better*', '*smaller is better*' and '*nominal is better*'. In this investigation the aim is to increase the amount of the base metal recovered to the concentrate, therefore SN ratios for "*larger is better*" were selected and calculated using response values i.e. percentage metal (Ni, Cu or Co) recovered. The SN ratio for this scenario was determined using:

$$SN = -10log\left[\frac{1}{n}\sum_{i=1}^{n}\left(\frac{1}{y_i^2}\right)\right] \quad (1)$$

Where $\boldsymbol{n}$ **is** the number of repetition of experiments, and $\boldsymbol{y_i}$ is the response value (recovery) of the i^{th} experiment.

2. 2. Flotation Procedure

All the flotation test-work was done using the Denver laboratory machine with a 1.5l stainless steel flotation cell. The required mass of nickel-copper sulphide ore material ground to 70% passing 75 µm was weighed and placed in the flotation cell. This was followed by the addition of distilled water to about 60% of the cell volume before the required volumes of 1% solutions of the collector; SIPX (s*odium isopropyl xanthate*) and depressant were added. The additions of the reagents solution were done using small (2-5ml) barrel medical syringes. More water was added to the cell to about 90% cell volume (about 10mm below the froth overflow lip). pH was then adjusted to the required set value using either sulphuric acid or sodium hydroxide. Two drops of the frother were then added before conditioning with the air valve closed for 4 minutes at 750rpm agitation. Following conditioning, the air valve was opened to maximum to allow aeration. After 3 minutes the froth was allowed to overflow and the float was kept at constant level mark (10mm below overflow lip) using distilled water from a wash bottle. Samples of the froth concentrate were collected after every 5minutes for 20 minutes. The collected samples were then sun-dried, weighed and assayed for nickel, cobalt and copper. The same drying procedure was also followed for the tailings. The experimental runs as described in Table 3 were run randomly and were done in duplicate. A total of 18 batch flotation test-works were done for this study.

The amount of metal (Ni, Cu or Co) recovered was calculated using equation (2) which is based on assays alone of the feed (***f***), tailings (***t***) and concentrate (***c***).

$$\%Metal\ Recovery = 100\left(\frac{c}{f}\right)\frac{(f-t)}{(c-t)} \quad (2)$$

2. 2. Analysis of Variance

Analysis of variance (ANOVA) is a standard statistical tool that can be used to interpret experimental data. A statistical test called an F-test, named after Fisher, is then used to see which process parameters have a significant effect on recovery. The contribution percentage of various parameters to the response can also be estimated by ANOVA. This identifies the parameter with the highest influence on metal recovery. The equations involved in the analysis of variance are presented in this section.

The total sum of squared deviations, $\boldsymbol{SS_T}$ was calculated based on the following formula:

$$\boldsymbol{SS_T = \sum_{i=1}^{N}(Y_i)^2 - \frac{(\sum_{i=1}^{N} Y_i)^2}{N}} \quad (3)$$

Where,

N is the total number of observations or experiments,

$\boldsymbol{Y_i}$ is the metal recovery for the *i*th experiment

The total sum of squared deviations is composed of two sources: the sum of squared deviations, $\boldsymbol{SS_P}$ due to each process parameter and the sum of squared error, $\boldsymbol{SS_E}$.

$$\boldsymbol{SS_P = \sum_{j=1}^{N_K}\frac{\left(\sum Y_j\right)^2}{N_K} - \frac{(\sum_{i=1}^{N} Y_i)^2}{N}} \quad (4)$$

Where ***p*** is one of the parameter of the experiment and ***j*** the level number of this parameter ***p***

The sum of squared error is therefore calculated as:

$$\boldsymbol{SS_E = SS_T - \sum SS_P} \quad (5)$$

The variance ($\boldsymbol{V_P}$), mean of squared deviations for each parameter ***p*** was computed using the following equation:

$$\boldsymbol{V_P = \frac{SS_P}{(N_K-1)}} \quad (6)$$

Where $\boldsymbol{N_K}$ is the number of levels for each parameter (3 in this case) and $\boldsymbol{N_K - 1 = f_P}$ is therefore the degrees of freedom for parameter, ***p***. The total degrees of freedom of the result ($\boldsymbol{f_T}$) are equal to the total number of experiments (9 in this case) minus one. The degrees of freedom for the experimental error ($\boldsymbol{f_E}$) is then given by:

$$f_E = f_T - \sum f_P \quad (7)$$

This is followed by the calculation of the variance ratio (F_{calc}) for each parameter, which is defined by

$$F_{calc} = \frac{V_P}{V_E} \quad (8)$$

Where V_E is the mean square (variance) of the error.

This is used in the evaluation of significance of the parameters on the response. The percentage contribution of each parameter to the response is then determined as:

$$\%PC = \frac{PSS_P}{SS_T} * 100 \quad (9)$$

where PSS_p is the pure sum of squares of each factor and is given by;

$$PSS_P = SS_p - f_i V_E \quad (10)$$

3. Results and Discussions

This section gives a summary of the findings for the flotation performance of nickel, copper and cobalt in the supplied sulphide ores. It is also dedicated to the analysis of data and identification of the optimal levels for all control parameters. Minitab 15.0 was used for statistical data analysis.

3.1 Base Metal Recovery

The average recovery of metals (nickel, copper and cobalt) by flotation for the various combinations of process parameters and levels is shown in Table 4. The highest recovery of nickel of 81% into the concentrate occurred in the 7th experiment run (pH = 10.15; collector dosage = 40g/t; % solids = 30; depressant dosage = 100g/t) and the lowest (38.3%) was recorded in the 5th experiment run (pH=8.15; collector dosage=60g/t; %solids=30; depressant dosage=80g/t). For copper the maximum recovery was 91.1% achieved in the 9th experimental run whilst lowest (25%) was recorded in the 1st experimental run. The maximum cobalt recovery (70.6%) was achieved in the 9th experimental run.

Table. 4. Experimental results for metal (Ni, Cu, Co) recovery.

Exp. No.	pH	Collector Dosage (g/t)	%Solids	Depressant dosage (g/t)	Ave. %Ni Recovery	Ave. % Cu Recovery	Ave. %Co Recovery
1	1 (6.15)	1 (40)	1 (20)	1 (80)	56.4	25.0	27.8
2	1 (6.15)	2 (60)	2 (25)	2 (100)	75.6	64.0	26.4
3	1 (6.15)	3 (80)	3 (30)	3 (150)	64.7	50.8	25.7
4	2 (8.15)	1 (40)	2 (25)	3 (150)	40.7	51.8	7.7
5	2 (8.15)	2 (60)	3 (30)	1 (80)	38.3	54.4	10.8
6	2 (8.15)	3 (80)	1 (20)	2 (100)	61.5	67.3	21.5
7	3 (10.15)	1 (40)	3 (30)	2 (100)	81.0	78.7	63.6
8	3 (10.15)	2 (60)	1 (20)	3 (150)	48.3	85.7	41.8
9	3 (10.15)	3 (80)	2 (25)	1 (80)	70.0	91.1	70.6

To determine the effect each parameter has on the response, the signal-to-noise ratio (SN) was calculated for each experiment. The SN ratio, based on '*larger is better'* (Eqn.1), for the base metal recoveries for all the experimental runs are shown in Table 5.

Table. 5. SN ratios for metal recovery based on 'larger is better'.

Exp. No.	pH	Collector Dosage (g/t)	%Solids	Depressant dosage (g/t)	SN ratio for Ni	SN ratio for Cu	SN ratio for Co
1	1 (6.15)	1 (40)	1 (20)	1 (80)	35.03	27.96	28.88
2	1 (6.15)	2 (60)	2 (25)	2 (100)	37.57	36.12	28.43
3	1 (6.15)	3 (80)	3 (30)	3 (150)	36.22	34.12	28.20
4	2 (8.15)	1 (40)	2 (25)	3 (150)	32.19	34.29	17.73
5	2 (8.15)	2 (60)	3 (30)	1 (80)	31.66	34.71	20.67
6	2 (8.15)	3 (80)	1 (20)	2 (100)	35.78	36.56	26.65
7	3 (10.15)	1 (40)	3 (30)	2 (100)	38.17	37.92	36.07
8	3 (10.15)	2 (60)	1 (20)	3 (150)	33.68	38.66	32.42
9	3 (10.15)	3 (80)	2 (25)	1 (80)	36.90	39.19	36.98

Using data in Table 5, the average SN ratios of each level of the four parameters for the flotation of nickel were calculated and listed in Table 6. Delta values, which show the relative significance of the factors, were also calculated as the difference between the maximum and minimum average values. Based on this, depressant dosage followed by pH under the experimental conditions tested were the most influencing factors affecting the flotation behaviour of nickel from the sulphide ore. Percentage solids had the least influence on flotability of the nickel.

Table. 6. Average SN values for nickel flotation at three levels of parameters and delta statics.

Code	Flotation parameter	Level 1	Level 2	Level 3	Delta(max-min)	Rank
$\bar{A}$	pH	36.28*	33.21	36.25	3.06	2
$\bar{B}$	Collector dosage	35.13	34.30	36.30*	2.00	3
$\bar{C}$	%Solids	34.83	35.55*	35.35	0.72	4
$\bar{D}$	Depressant dosage	34.53	37.17*	34.03	3.14	1

* Optimum condition

The level of a parameter with highest average SN ratio corresponds to a better performance and gives the best combination level. Therefore, the optimal levels of flotation parameters are the ones with the greatest average SN ratio. The optimum levels of parameters for recovery of nickel are pH, 6.15 (Level 1); collector dosage, 80g/t (Level 3); %solids, 25 (Level 2); and depressant dosage, 100g/t (Level 2), asterixed figures in Table 6. A plot of the graph of the parameter against its response on each level is referred to as the main effect and it indicates the general trend of influence of each parameter. Fig.2 shows the effect of the process parameters on flotation recovery of nickel.

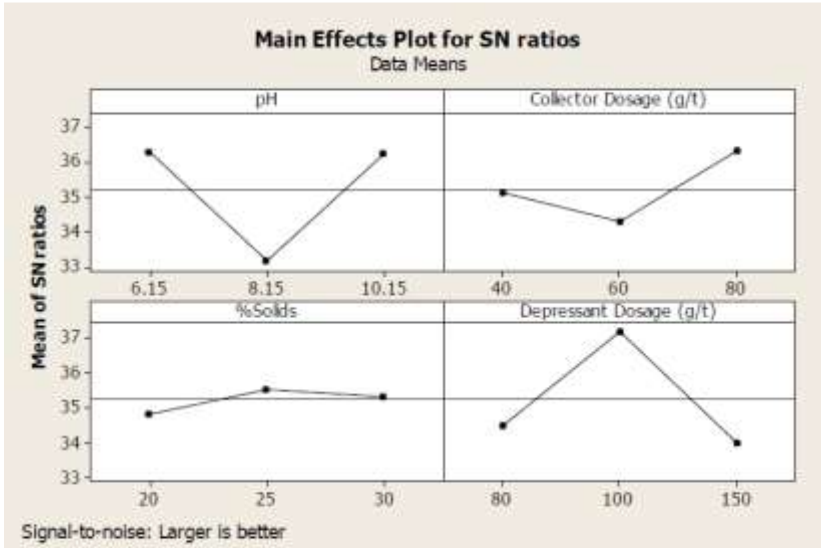

Fig.2. Main effect of process parameter on nickel recovery.

Delta values in Table 7 show that pH has the most relative significance on the flotation behaviour of copper and is followed by collector dosage, which is ranked second. Percentage solids show the least relative significance. The optimum levels for copper recovery are pH, 10.15 (level 3); collector dosage, 80g/t (level 3); percentage solids, 25 (level 2); and depressant dosage, 100g/t (level 2).

Table. 7. Average SN values for copper flotation at three levels of parameters and delta statics.

	Flotation parameter	Level 1	Level 2	Level 3	Delta (max-min)	Rank
$\bar{A}$	pH	32.73	35.19	38.59*	5.86	1
$\bar{B}$	Collector dosage	33.39	36.50	36.62*	3.23	2
$\bar{C}$	%Solids	34.39	36.53*	35.58	2.14	4
$\bar{D}$	Depressant dosage	33.95	36.87*	35.69	2.92	3

* Optimum condition

Fig.3 shows the main effects of process parameters on copper flotation.

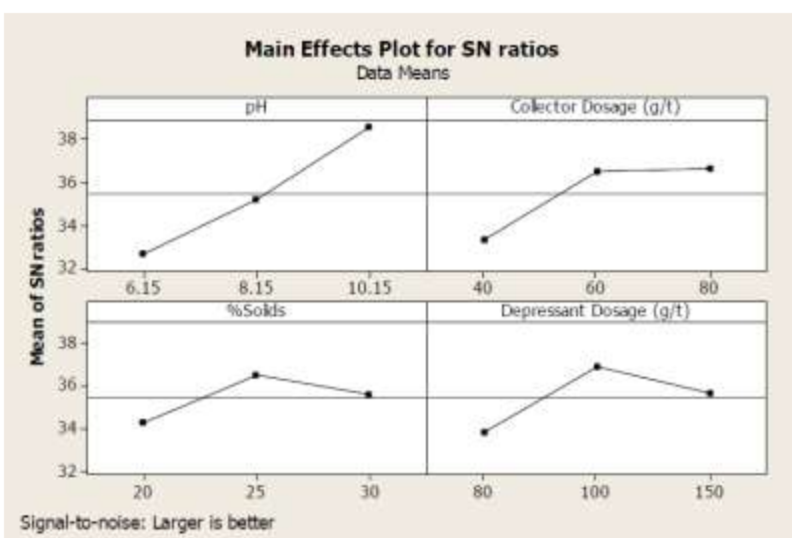

Fig.3. Main effect of process parameter on copper recovery

Delta values for cobalt in Table 8 also show pH as the most influencing parameter and percentage solids as the least influencing parameter affecting its flotation behaviour. The asterixed values in Table 8, i.e. pH level of 3 (10.15), collector dosage level 3 (80g/t), percentage solids level 1 (20%) and depressant dosage level 2 (100) gives the optimum recovery of cobalt into the concentrate.

Table. 8. Average SN values for cobalt flotation at three levels of parameters and delta statics.

Code	Flotation parameter	Level 1	Level 2	Level 3	Delta (max-min)	Rank
$\bar{A}$	pH	28.50	21.68	35.16*	13.48	1
$\bar{B}$	Collector dosage	27.56	27.17	30.61*	3.44	3
$\bar{C}$	%Solids	29.32*	27.71	28.31	1.61	4
$\bar{D}$	Depressant dosage	28.84	30.38*	26.12	4.26	2

* Optimum condition

The change in response performance with change in process parameter is shown in Fig.4.

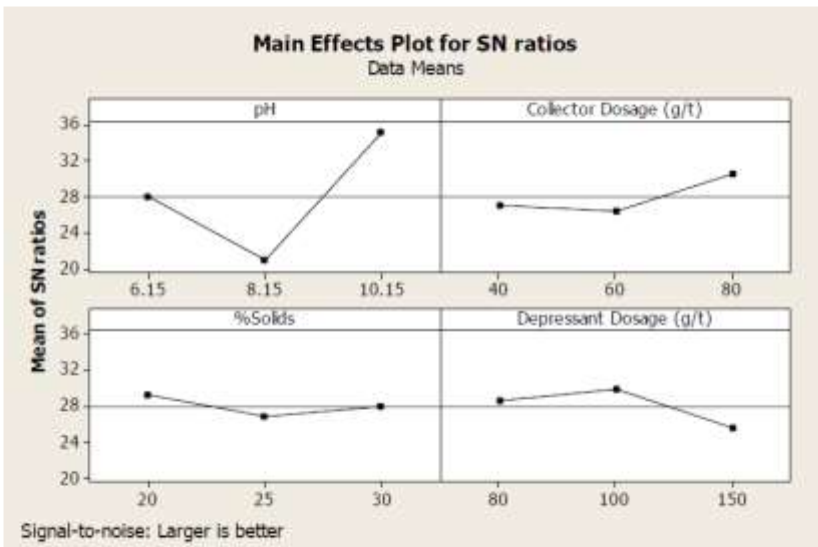

Fig.4. Main effect of process parameters on cobalt recovery.

3.2 Analysis of Variance (ANOVA)

The parameters which significantly affected the base metal recovery were investigated using the analysis of variance (ANOVA). The contribution percentage of different parameters on nickel, copper and cobalt recovery as obtained by ANOVA are presented in Table 6, 7 and 8, respectively. These percentage values also confirm the relative importance of each parameter. For example, it can be seen from Table 6 that the pH (A), collector dosage (B) and depressant dosage (D) affect nickel recovery by 41.84%, 12.26% and 38.25% in the flotation of nickel-copper sulphide ore respectively. Since the degree of freedom for the error term is zero, it was necessary to pool the parameter having less influence (%solids in this case) for the results to be interpreted.

Based on ANOVA and at 95% confidence level, pH has significant effect on the flotation recovery of both nickel and cobalt from the sulphide ore whilst depressant dosage has significant effect only on nickel recovery. None of the tested parameters significantly affected the recovery of copper at the tested same confidence level.

Table. 9. ANOVA table for nickel recovery after pooling (at 95% confidence level).

Code	Parameter	Degree of freedom	Sum of squares	Mean Squares, V_i	F_{calc} ratio	P-Value	Pure Sum of Squares	%PC
A	pH	2	18.64677	9.323383	22.89789	0.0418	17.83242	41.84
B	Collector Dosage	2	6.038956	3.019478	7.415726	0.1188	5.224611	12.26
C	%Solids	2	0.834956	0.417478	-			-
D	Depressant dosage	2	17.11776	8.558878	21.02029	0.0454	16.30341	38.25
	Error	0	0	-	-			-
	(Pooled Error)	(2)	(0.814344)	(0.40717)			3.257378	(7.64)
	Total	8	42.61782					

Table. 10. ANOVA table for copper recovery after pooling (at 95% confidence interval).

Code	Parameter	Degree of freedom	Sum of squares	Mean Squares	F_{calc} ratio	P-Value	Pure Sum of Squares	%PC
A	pH	2	51.90207	25.95103	7.524001	0.1173	45.00387	49.02
B	Collector Dosage	2	20.12187	10.06093	2.916974	0.2553	13.22367	14.40
C	%Solids	2	6.8982	3.4491	-	-		
D	Depressant dosage	2	12.88807	6.444033	1.868323	0.3486	5.989867	6.52
	Error	0	0					
	Pooled Error	(2)	(6.8982)	(3.4491)			0(27.5928)	(30.06)
	Total	8	91.8102					

Table. 11. ANOVA table for cobalt recovery after pooling (at 95% confidence interval).

Code	Parameter	Degree of freedom	Sum of squares	Mean Squares	F_{calc} ratio	P-Value	Pure Sum of Squares	%PC
A	pH	2	272.31000	136.15500	69.16062	0.0143	268.3726	82.44
B	Collector Dosage	2	21.26269	10.63134	5.400246	0.1562	17.32533	5.32
C	%Solids	2	3.937356	1.968678	-	-	-	-
D	Depressant dosage	2	28.01076	14.00538	7.114104	0.1232	24.0734	7.40
	Error	0	0					
	Pooled Error	(2)	(3.937356)	(1.968678)			0(15.74942)	(4.84)
	Total	8	325.5208					

3.3 Prediction of the Optimum Performance

Once the optimum parameters have been determined, the optimum performance of the response at these parameters can be predicted. The predicted SN ratio ($\boldsymbol{SN_{opt}}$) of recovery of the metal (Ni, Cu &Co) at optimum condition was calculated by adding the mean performance to the contribution of each parameter at the optimum level using the following equation.

$$\boldsymbol{SN_{opt}} = \frac{\boldsymbol{SN_T}}{\boldsymbol{N}} + \left(\bar{\boldsymbol{A}}_{\boldsymbol{opt}} - \frac{\boldsymbol{SN_T}}{\boldsymbol{N}}\right) + \left(\bar{\boldsymbol{B}}_{\boldsymbol{opt}} - \frac{\boldsymbol{SN_T}}{\boldsymbol{N}}\right) + \left(\bar{\boldsymbol{C}}_{\boldsymbol{opt}} - \frac{\boldsymbol{SN_T}}{\boldsymbol{N}}\right) + \left(\bar{\boldsymbol{D}}_{\boldsymbol{opt}} - \frac{\boldsymbol{SN_T}}{\boldsymbol{N}}\right) \quad (11)$$

where,

SN_T : grand total of average SN ratio for each experiment,

N : total number of experiments,

$\bar{A}_{opt}$: average SN ratio for parameter A at its optimum level,

$\bar{B}_{opt}$: average SN ratio for parameter B at its optimum level,

$\bar{C}_{opt}$: average SN ratio for parameter C at its optimum level, and

$\overline{D}_{opt}$: average SN ratio for parameter D at its optimum level.

Since the sum of squares due to the parameter C is small as well as used to estimate the error variance, this term is not included in the prediction of the optimum recovery. Table 12 shows the optimum level of each parameter to achieve the highest Ni recovery and the corresponding recoveries of Cu and Co; highest Cu recovery and corresponding recoveries of Ni and Co; and the highest Co recovery and corresponding Ni and Co recoveries.

Table. 12. Predicted SN and metal recoveries at optimum conditions.

Target	**A**	**B**	**C**	**D**	**Predicted value for Ni**		**Predicted value for Cu**		**Predicted value for Co**	
					SN	**Recovery**	**SN**	**Recovery**	**SN**	**Recovery**
Ni recovery-max	6.15	80	-	100	39.27	91.94	35.22	57.68	32.59	42.61
Cu recovery-max	10.15	80	-	100	39.24	91.62	41.08	100	39.25	91.73
Co recovery-max	10.15	80	-	100	39.24	91.62	41.08	100	39.25	91.73

4. Conclusion

The following conclusions are drawn from the present study within the levels of process parameters selected:

- The optimum conditions for maximum Ni recovery are: collector dosage, 80g/t; pH, 6.15; %solids, 25; and depressant dosage, 100g/t. For maximum Cu recovery the optimum conditions are: collector dosage, 80g/t; pH, 10.15; %solids, 25; and depressant dosage, 100g/t whilst for Co recovery they are: collector dosage, 80g/t; pH, 10.15; %solids, 25; and depressant dosage, 100g/t.
- The optimal levels of parameters for the maximum recovery of all the three base metals is achieved with a pH, 10.15; collector dosage, 80g/t; percentage solids, 25% and depressant dosage of 100g/t.
- Relative significance of flotation parameters (based on difference between max and min. average values) indicates that pH has the most significant effect on the recovery of nickel, copper and cobalt during flotation.
- Based on ANOVA and at 95% confidence level, pH has significant effect on the flotation recovery of both nickel and cobalt from the sulphide ore whilst depressant dosage has significant effect only on nickel recovery. None of the factors significantly affect the recovery of copper at the tested confidence level of 95%.
- pH has the major contribution in controlling the flotation of the base metals (Ni, Cu and Co) from the nickel-copper sulphide ore. Depressant dosage also plays a significant effect in controlling the flotability of nickel (~40% contribution to overall nickel recovery). The range of percentage solids considered for this study had the least contribution on recovery of base metals.

Acknowledgements

The authors would like to acknowledge Trojan Nickel Mine for supplying the ore material used for this study.

References

Abali, Y., Copur, M. and Yavuz, M. (2006). Determination of the optimum conditions for dissolution of magnesite with H_2SO_4 solutions, Indian Journal of Chemical Technology, Vol.13, pp. 391-397

Bagchi, T.P. (1993). Taguchi methods explained: Practical steps to robust design, Prentice-Hall of India Private Limited, New Delhi

Göktepe, F. (2002). Effect of pH on pulp potential and sulphide mineral flotation, Turkish J. Eng. Sci. 26, pp. 309-318

Gopalsamy, B.A., Mondal, B. and Ghosh,S. (2009). Taguchi method and ANOVA: An approach for process parameters optimization of hard machining while machining hardened steel, Journal of scientific and Industrial Research, Vol. 68, pp. 686-695

Haghi, H., Ghadyani, A., Biranvand, B., and Shafaei, S.Z. (2009). Optimization of Apatite flotation using Taguchi method, 7th industrial Minerals Symposium and Exhibition, 25-27 February, Turkey

IIyas, S., Bhatti, H.N., Bhatti, I.A., Sheikh, M.A., and Ghauri, M.A. (2010). Bioleaching of metal ions from low grade sulphide ore: Process optimization by using orthogonal experimental array design, African Journal of Biotechnology, Vol. 9(19), pp. 2801-2810

Kabuba, J., Muzenda, E., and Ntuli, F. (2011). Examination of flotation reagents suitable for nickel concentrator plant, 2nd International Conference on Chemistry and Chemical engineering, IPCBEE, Vol.14, Singapore, pp. 65-69

Kamaruddin, S., Khan,Z.A., and Wan, K.S. (2004). The use of the Taguchi method in determining the optimum plastic injection moulding parameters for the production of a consumer product, Jurnal Mekanikal, Bil.18, pp. 98-110

Muzenda, E. (2010). An investigation into the effect of water quality on flotation performance, World Academy of Science, Engineering and Technology 45, pp. 237-241

Muzenda, E., Afolabi, A.S., Abdulkareem, A.S. and Ntuli, F. (2011). Effect of pH on the Recovery and grade of base metal sulphides (PGMs) by flotation, Proceedings of the World Congress on engineering and Computer Science 2011 Vol II, *WCECS 2011*, October 19-21, San Francisco, USA

Nashwa, V.M. (2007). The flotation of high talc-containing ore from the Great Dyke of Zimbabwe, MSc Thesis, University of Pretoria

Pérez-Garibay, R., Ramírez-Aguilera, N., Bouchard, J., and Rubio, J. (2014). Froth flotation of sphalerite: Collector concentration, gas dispersion and particle size effects, Minerals Engineering 57, pp. 72-78

Rama, R.S. and Padmanabhan, G. (2012). Application of Taguchi methods and ANOVA in optimization of process parameters for metal removal rate in electrochemical machining of Al/5%SiC composites, International Journal of engineering Research and Application (IJERA), Vol.2, Issue 3, pp. 192-197

Saleh, A-H.M., Ramadan, A.M., and Moharam, M.R. (2008). Beneficiation of Egyptian Abu-Swayel copper ore by flotation, Physicochemical Problems of Mineral Processing, 42, pp. 119-130

Sapakal, S.V.and Telsang, M.T. (2012). Parametric optimization of MIG welding using Taguchi Design Method, International Journal of Advanced Engineering Research and Studies, Vol.1, Issue IV, pp. 28-30

Shuhua, H. (2006). Depression of pyrite in the flotation of copper ores, DPhil Theses, University of South Australia, pp. 20

Temur, H., Yartasi, A. and Kocakeri, M.M. (2009). Determination of the optimum conditions of the dissolution of chalcopyrite concentrate in aqueous solutions saturated with chlorine gas, 1st International Symposium on Sustainable Development, June 9-10, Sarajevo