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Acidic Reaction of Waste Aluminum Foil for Alumina Production

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ABSTRACT

Batch experiments were performed in order to evaluate the most effective conditions of reaction between aluminum foil waste and hydrochloric acid using a statistical model based on 2^3 full factorial design. The three factors investigated were aluminum foil waste particle size, aluminum foil to acid solution ratio, and acid solution concentration. The optimization of the factors to obtain maximum conversion was carried out by incorporating surface plots. A first order model was elaborated and indicated that the maximum observed conversion reaches 97.6% compared with 95.69% calculated conversion under the following conditions: solid to liquid ratio of 0.0127 g foil/g HCl solution, aluminum foil particle size of 10 mm and 2 M acid concentration. XRF showed that the obtained alumina has a purity of 90.13% by weight.

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1. Introduction

The first commercial production of aluminum foil started in the United States by 1913 where it was used for wrapping life savers, candy bars, and similar items. Aluminum foil is usually produced as a thin-rolled sheet of alloyed aluminum varying in thickness from about 4 –150 µm. Its uses developed from paperboard in 1921 to household foil then to heat sealable foil to reach formed, semi-rigid, containers by mid twentieth century [1]. One main reason for its expanded uses is the extremely low permeability of foils of thickness above 15 µm which is way lower than that of most food packaging plastic films [2].

On the other hand, aluminum is produced worldwide mainly through bauxite ores. This production increased from 183 million metric tons in 2006 to reach 270 Mt in 2015. On the other hand, the aluminum US consumption also increased through the same period from 45 Mt to 20Mt with a growth rate of about 4% per year. Most of the metal is produced by the Bayer process essentially involving the action of an alkaline solution on bauxite. The problem with that process is the huge amount of energy involved (14 MWh per ton) and the formation of numerous environmentally unfriendly wastes such as tailings, red mud besides gaseous emissions of perfluorocarbon, and CO_2 [3,4].

It appears therefore that recycling of aluminum waste can represent a sustainable solution for the environmental issue. It has been reported that recycling of 1 ton of aluminum saves 8 tons of bauxite, 4 tons of chemical products besides 14 MW of electricity [4]. Owing to the fact that the Egyptian territory contains very limited bauxite reserves [5]. It was necessary to find other routes for producing alumina (Al_2O_3) which is mainly known for its use in the production of Aluminum, and employed in many other applications like glass industry, water purification, refractory materials and ceramics [6].

Although converting aluminum foil into useful products is an important environmental issue as mentioned above, the studies performed in this research area are limited [7]. Recently, Visbal et al used Al foil waste in hydrogen production by converting it into active Al powder that reacts with water or by using $Ca(OH)_2$ to remove the surface oxide layer and initiate the hydration reaction [8].

El Amir et al [9] prepared nanoscale single crystalline Ƴ-Alumina powder from aluminum foil waste precursor via co-precipitation method using Ammonium Hydroxide NH_4OH as a precipitant, while Osman et al [10] prepared alumina from aluminum foil scrap using 6 M hydrochloric acid solution to form aluminum Chloride solution from which the hydroxide was precipitated using ammonia solution. The pale off-white precipitate was then filtered, washed, dried at 120 °C and calcined at 550 °C for 4 hours in a muffle furnace. This work however stopped short of investigating the effect of the parameters affecting the dissolution reaction.

The present work aims at using a statistical approach, namely the factorial design technique to determine the most effective conditions for alumina recovery from aluminum foil waste reaction with hydrochloric acid. This technique has been successfully used in several industrial applications. The effect of the following variables on alumina recovery has been investigated: Acid concentration, foil particle size, and acid to foil ratio.

2. Experimental Methods

2.1 Materials

The raw materials used in this study were aluminum foil waste packages collected from home use, hydrochloric acid (37%) analytical grade, and ammonium hydroxide NH_4OH (25%) supplied by El-Gomhoreya Co., Cairo, Egypt.

2.2 Experimental Work

First the used foil packages were washed, and cut to the required size using a rotary knives cutter. The required amount of HCl was then added to the stoichiometric amount of Al foil, and the reaction allowed to occur for 5 minutes through the following rapid exothermic corrosion reaction:

$$Al+6HCl \rightarrow 2AlCl_3+3H_2 \qquad \Delta H = -527.5\ kJ/mol. \qquad (1)$$

The suspension was immediately filtered using a glass filter to separate unreacted materials. Aluminum chloride solution was obtained as filtrate. Ammonium hydroxide solution (25%) was then added to the filtrate drop wise until the pH reached 10 resulting in precipitation of $Al(OH)_3$ by the following reaction:

$$AlCl_3+NH_4OH \rightarrow A(OH)_3+3NH_4Cl \qquad (2)$$

The gelatinous precipitate formed was separated from the solution using filter paper, dried in for one hour at a temperature of 250 °C, and finally was calcined at 600 °C for one hour in a laboratory muffle furnace to produce alumina as follows:

$$2A(OH)_3 \rightarrow Al_2O_3+3H_2 \qquad (3)$$

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2.3 The Factorial Design

The high and low levels defined for the 2^3 factorial design are listed in Table 1. The choice of the low and high levels for the factors was made according to the following criteria: Acid to foil ratio was chosen to keep suitable fluidity of the resulting mixture whereas the particle size range was tentatively selected according to common practice figures used in recycling.

Table 1 Experimental ranges of investigated independent variables

Variable	Symbol	Unit	Lower level	Higher level
Solid to liquid ratio	X_1	g/g	0.0127	0.0153
Particle size	X_2	mm	10	3
Acid concentration	X_3	M	2	6

The conditions of the conducted experiments can be summarized in the following Table 2.

Table 2 The experimental conditions

Exp. No.	S/L Ratio	Particle Size (mm)	Acid Conc. (M)
1	0.0127	10	2
2	0.0153	10	2
3	0.0127	30	2
4	0.0153	30	2
5	0.0127	10	6
6	0.0153	10	6
7	0.0127	30	6
8	0.0153	30	6

Three replicate experiments were performed at the center of design at S/L ratio of 0.014, particle size of 20 mm, and acid ratio of 4 M.

3. Results and Discussion

3.1 Factorial Design Calculations

The application of orthogonal factorial design technique involves the following steps [11, 12].

Coded variables are next defined for each of the three-parameter investigated so as to obtain – 1, +1 or 0 values for minimum, central, and maximum levels respectively as indicated in Table 3.

Table 3 Coded variables

Variable	Symbol	Coded symbol, X
Solid to liquid ratio	S/L	$\frac{(S/L)-0.014}{0.0013}$
Particle size	D_p	$\frac{D_p-20}{10}$
Acid concentration	C	$\frac{C-4}{2}$

Table 4 Coded matrix

X_0	X_1	X_2	X_3	X_1X_2	X_2X_3	X_3X_1	$X_1X_2X_3$
1	-1	-1	-1	1	1	1	-1
1	1	-1	-1	-1	1	-1	1
1	-1	1	-1	-1	-1	1	1
1	1	1	-1	1	-1	-1	-1
1	-1	-1	1	1	-1	-1	1
1	1	-1	1	-1	-1	1	-1
1	-1	1	1	-1	1	-1	-1
1	1	1	1	1	1	1	1
1	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0

A design matrix M is then established involving 2^3 combinations of – 1, and +1 values of the 3 variables. The alumina recovery for all 8 experimental conditions is then measured, and a column vector Y (Conversion) is obtained. In first order design the regression equation for coded variables takes the form:

$$y = a_0 + \sum_{1=1}^{5} a_i x_i + \sum_{i=1,j=1,i\neq j}^{5} a_{ij} x_i x_j + \sum_{i\neq j\neq k}^{5} a_{ijk} x_i x_j x_k + \sum_{i\neq j\neq k\neq l}^{5} a_{ijkl} x_i x_j x_k x_l + a_{12345} x_1 x_2 x_3 x_4 x_5 \quad (4)$$

This equation contains 8 constants corresponding to a coefficient column vector A. The value of the elements of vector A can be obtained from the Eq.(5),

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$$A = M^{-1}.Y \quad (5)$$

where, M represents the following 8×8 matrix including the coded variables defined by Table 3 and Y is the column vector consisting of the results of reaction yield of the 8 runs.

11 experimental runs were performed at the conditions specified in Table 5 involving three replicates at the center point of design. The values of the coefficients in the coded regression Eq.(4) could then be obtained by applying Eq.(5).

After applying the t – test, some of the coefficients were eliminated for being statistically insignificant. When the coded variables then replaced by original variables according to their definition in Table 3, the following regression equation was obtained for percent conversion,

$$\text{Conversion (Y)} = 290.14 - 13715.39\, S/L - 4.42\, D_p - 18.5\, C + 272.46\, (S/L).D_p + 0.1538\, D_p.C + 1107.31 (S/L).C \quad (6)$$

Once the regression equation has been established and non-significant coefficients eliminated, the validity of the expression can be tested by calculating the determination coefficient R^2 which was found to be 0.9548, meaning that 95.48% of the variation in conversion is due to the variations in the three parameters.

Table 5 Design conditions, and observed alumina recovery (first order model)

Run	S/L	X_1	D_p	X_2	C	X_3	Y (observed)
1	0.0127	-1	10	-1	2	-1	97.64
2	0.0153	+1	10	-1	2	-1	73.53
3	0.0127	-1	30	+1	2	-1	79.41
4	0.0153	+1	30	+1	2	-1	72.06
5	0.0127	-1	10	-1	6	+1	74.12
6	0.0153	+1	10	-1	6	+1	64.12
7	0.0127	-1	30	+1	6	+1	70.78
8	0.0153	+1	30	+1	6	+1	72.35
9	0.014	0	20	0	4	0	88.05
10	0.014	0	20	0	4	0	86.70
11	0.014	0	20	0	4	0	89.67

The observed conversions were compared with the conversions calculated from the deduced regression equation. The results can be summarized in Fig. 1 which reveals excellent concordance between the two sets of values.

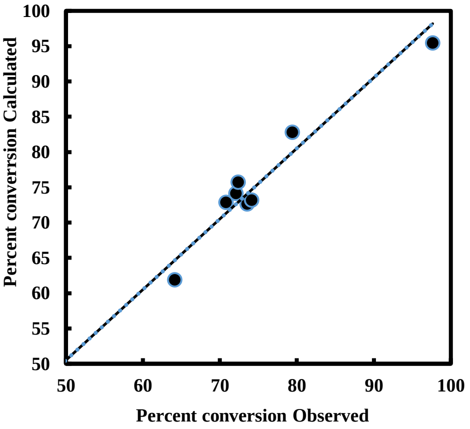

Fig. 1 Observed conversion versus predicted conversion

3.2 Surface Plots

These plots can be obtained by computations using developed response models and adequate software (XLSTAT free trial). From Fig. 2, we can observe that the conversion decreased as the S/L ratio increased as could also be deduced from the negative coefficient obtained in Eq.(6). This is since when solid to liquid ratio was increased, the amount of aluminum solid per unit liquid increased causing a decrease in recovery [13]. The same trend can be observed at acid concentration of 4 M and 6 M.

Also, from Fig. 3, it can be observed that the conversion increased as the particle size decreased. That can be explained by the increased surface area exposed to the reaction.

From Fig. 4, it can also be observed that: the conversion decreased as the acid concentration increased. This can be explained by the formation of an oxide passive layer on the surface of aluminum. The aluminum oxide layer is chemically bound to the surface and seals the core aluminum from any further reaction [14].

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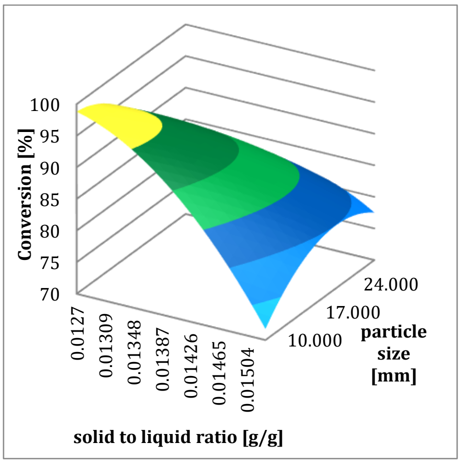

Fig. 2 The effect of S/L Ratio on the conversion and particle size at 2 M acid concentration

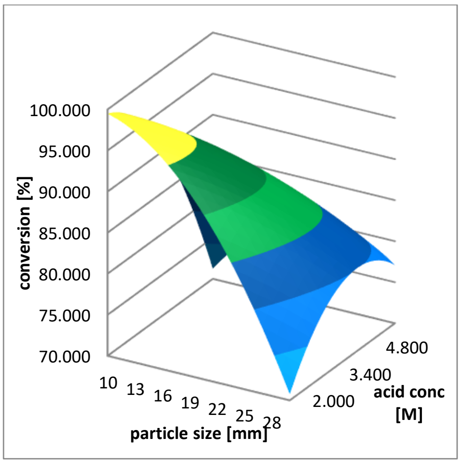

Fig. 3 The effect of particle size and acid concentration on the conversion at S/L ratio = 0.0127

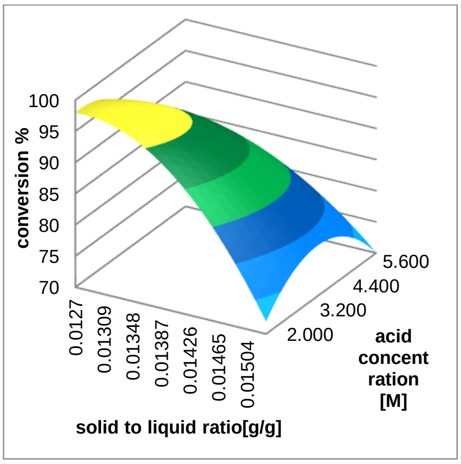

Fig. 4 The effect of solid to liquid ratio and acid concentration on the conversion at particle size of 1 cm

The experimentally prepared Alumina was analyzed using Axios advanced, Sequential WD_XRF Spectrophotometer, and the result was as follows in Table 6.

Table 6 Produced alumina analysis

Main Constituents	g/g (mass%)
SiO_2	0.45
TiO_2	0.02
Al_2O_3	90.13
$Fe_2O_3^{tot.}$	0.63
CaO	0.09
Na_2O	0.04
K_2O	0.01
SO_3	0.04
Cl	3.13
LOI	5.39
MnO	0.006
NiO	0.024
CuO	0.014
ZnO	0.005
Ga_2O_3	0.016

4. Conclusion

2^3 Full factorial design was used to assess the best conditions for alumina recovery from aluminum foil waste by reaction with hydrochloric acid. The investigated parameters were: solid to liquid ratio, foil particle size, and acid concentration. A first order model was first elaborated, and a regression equation obtained that showed a strong determination coefficient (0.9548). The maximum observed conversion reaches 97.6% compared with 95.7% calculated conversion under the following conditions: solid to liquid ratio of 0.0127 g foil/g HCl solution, aluminum foil particle size of 1 cm, and 2 M acid concentration. XRF showed that the obtained alumina has a purity of 90.13 g/g (mass %).

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