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Artificial neural network vs. nonlinear regression for gold content estimation in pyrometallurgy

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ABSTRACT

Pyrometallurgy is often used in the industrial process for treating gold-bearing slime. Slag compositions have remarkable influences on gold recovery and gold content in slag. In this paper, the relationships between the slag compositions in the soda–borax–silica glass-salt system and the gold content in the slag are investigated by using nonlinear regression and artificial neural network. A neural network model for estimating the gold contents of different slag compositions is presented, including the neural network type, structure and its learning algorithms. The study indicates that the three-layer back propagation neural network model can be applied to estimate gold content in the slag. Compared with the traditional regression methods, the neural network has many advantages.

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1. Introduction

In the gold manufactory industry, pyrometallurgical treatment (Marsden & House, 2006) is often adopted to process gold-bearing slime or gold slime for short. That is, by adding appropriate fluxing agents at high temperature, precious metals are separated from oxides and gangue which comprise the remains in the slag. In this way, gold–silver alloys are obtained by pyrometallurgy. In the smelting process, slag compositions essentially determine the gold content in the slag, hence, the recovery of gold. To upgrade the recovery of gold as well as to minimise gold content in the slag, it is of great importance to study the relationships between slag compositions and gold content in the slag in the smelting process of gold slime.

However, smelting gold slime is a complicated process which involves the chemical reactions in multi-phases. Therefore, it is usually hard to describe the relationships between slag compositions and gold content in the slag explicitly. Currently, statistical methods such as linear or nonlinear regression methods are generally used to deal with this problem (Yuan, 1995). The application of such a method requires that some presumption be made about the form of distributions of data or the functional relations among the parameters concerned. Apparently, it is difficult to obtain confident results of high precision under certain circumstances, for instance, the distributions of data are too complicated to estimate, or the relations among the concerned parameters are un-determinable, or there are too many parameters, or the discreteness of the data is too great.

From an industrial point of view, prediction of gold content in the slag with different slag compositions before smelting can be an important object for maximising gold recovery and lowering production cost. In this research, the soda–borax–silica glass-salt system (Yuan, 1995) is adopted as slag compositions in the treatment of gold slime. Because of the mentioned difficulties that are faced when smelting gold slime, we have decided to search for a new model to predict gold content in the slag in addition to the traditional nonlinear regression. On the other hand, the neural network has proven to be a powerful tool in many areas including industrial processes (Schlang, Lang, Poppe, Runkler, & Weinzierl, 2001), prediction of materials properties such as steel (Bahrami, Mousavi Anijdan, & Ekrami, 2005; Capdevila, Garcia-Mateo, Caballero, & García de Andre's, 2006; Guo & Sha, 2004). In addition, there are many other reports that the neural network approach has used in material science-based research (Sha & Edwards, 2007). Artificial neural networks (ANNs) are now well established, and are prominent in the literature. However, a review of current research on pyrometallurgy indicates that its application to pyrometallurgical processes of gold has not been developed to the best of our knowledge.

As mentioned above, the ANN approach can be a very good choice in this regard, as it exhibits a significant ability in simu-

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lating and controlling various processes in which different parameters are interacting simultaneously. Therefore, the aim of this study is threefold: (i) to establish the relationships between the gold content in the slag and the use of the slag composition system by using the traditional linear regression method; (ii) to establish an ANN model that can predict the gold content in slag when adopting different slag compositions; (iii) to compare these two ways to identify the advantages and disadvantages, if any.

2. The way of trapping gold in slime and nonlinear regression

The intermediate frequency induction furnace is often used in pyrometallurgy to produce gold from gold slime. In the smelting process, fluxing agents must be added to separate the gold–sliver phase from others. In industries, the common chemicals used for this purpose include soda, borax, silica glass, and fluorite. The negative aspect in doing so is the high gold concentration in the slag. Sometimes, it can be as high as up to 300–500 g/t (Yuan, 1995). Cyaniding the slag can help further recovery of gold, but as indicated by Yuan (1995), the recovery rate of gold is usually substantially low (often <30%). In order to improve the overall recovery of gold, appropriate fluxing agents should be used. In addition, the amounts of fluxing agents and their combinations should be optimized when smelting gold-bearing slime. In this research, the ternary system B_2O_3–SiO_2–Na_2O is used as the basic slag type, and small-scale pyrometallurgical experiments in the melting pot have been carried out to simulate the industrial processes. The detailed experimental methodology can be found in Yuan (1995). The experiments are organised by using the orthogonal design of the four-factor regression of second degree. The experimental results are listed in Table 1.

As seen in Table 1, a total of 25 experiments were done by varying the combinations of slag compositions. The corresponding gold content in each experiment is also measured ranging from ca. 100 g/t to ca. 660 g/t.

By using nonlinear regression technique, a regression formula for estimating the gold content is deduced for these results as the follows:

$$y = -66.84x_1 - 7.1x_2 - 19.32x_3 - 48.75x_4 - 42.92x_1x_2 - 0.094x_1x_3 - 12.17x_1x_4 + 18.47x_2x_3 + 7.02x_2x_4 + 61.72x_3x_4 + 66.98x_1^2 + 43.44x_2^2 + 69.75x_3^2 - 5.38x_4^2 + 152.36. \quad (1)$$

This formula can be used for calculating or estimating the gold content in the slag for the completed experiments, of course, errors will be observed, and we will come back to this later.

3. Artificial neural networks

In this paper, an artificial neural network model is developed for estimating or predicting gold content in the slag in pyrometallurgy. Artificial neural network is a network with nodes or neurons analogous to the biological neurons. The nodes are interconnected to the weighted links and organised in layers. The performance of a neural network depends mainly on the weights of its connections. The knowledge is represented and stored by the weights (strength) of the connections between the neurons (processors). If correct weights can be trained then an ANN can do an exceptional function. There have been many studies on the application of neural networks involving many concrete applications such as pattern recognition, pattern classification and nonlinear problems.

Although there are different types of ANN, feed-forward multilayer perception (MLP) is probably the most widely used due to its powerful modelling capability (Hornik, Stinchcombe, & White, 1989; Kurkova, 1992). It will be shown that MLP is a suitable type of neural network for estimating gold content in the slag. Fig. 1 shows a typical feed-forward multilayer perception. It consists of four layers: the input layer, the output layer and two hidden layers. The neurons in the input layer take the information on slag compositions x_i (independent variables), and the output layer generates the outcomes of gold content in slag o_i (dependent variables). The nonlinear relationships between the dependent and the independent variables can be expressed by the following formula:

$$o_j = f_j\left(\sum w_{ij} f\left(\sum w_{rg} f\left(\sum w_{ir}\frac{1}{1+e^{-x_i}} - \theta_r\right) - \theta_g\right) - \theta_j\right), \quad (2)$$

Table 1
Testing results for different compositions of soda–borax–silica glass-salt slag system.

Sample no.	Soda (%)	Borax (%)	Silica glass (%)	Salt (%)	Gold content in slag (g/t)
1	12.9	42.9	14.4	2.9	506.4
2	12.9	42.9	14.4	17.1	272.7
3	12.9	42.9	35.6	2.9	267.0
4	12.9	42.9	35.6	17.1	397.1
5	12.9	57.1	14.4	2.9	657.0
6	12.9	57.1	14.4	17.1	285.0
7	12.9	57.1	35.6	2.9	323.8
8	12.9	57.1	35.6	17.1	468.6
9	27.1	42.9	14.4	2.9	510.0
10	27.1	42.9	14.4	17.1	252.0
11	27.1	42.9	35.6	2.9	293.3
12	27.1	42.9	35.6	17.1	170.6
13	27.1	57.1	14.4	2.9	228.7
14	27.1	57.1	14.4	17.1	170.5
15	27.1	57.1	35.6	2.9	258.9
16	27.1	57.1	35.6	17.1	172.3
17	10.0	50.0	25.0	10.0	362.9
18	30.0	50.0	25.0	10.0	210.5
19	20.0	40.0	25.0	10.0	253.3
20	20.0	60.0	25.0	10.0	225.9
21	20.0	50.0	10.0	10.0	241.2
22	20.0	50.0	40.0	10.0	343.3
23	20.0	50.0	25.0	0.0	183.9
24	20.0	50.0	25.0	20.0	100.0
25	20.0	50.0	25.0	10.0	151.2

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