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Impact of material and energy flow variation-based iron/steel ratio on production cost

Lu Biao[1] Chen Guang[2] Chen Demin[2] Yu Weiping[1] Ding Yi[3]

([1]School of Energy and Environment, Southeast University, Nanjing 210096, China)
([2]School of Civil Engineering, Anhui University of Technology, Ma'anshan 243032, China)
([3]Ma'anshan Iron & Steel Co. Ltd., Ma'anshan 243000, China)

Abstract: This paper establishes a model for the production cost of iron and steel enterprise. The variation rule of the production cost versus the iron/steel ratio for two cases, namely, fixed steel production and a fixed amount of molten iron, is analyzed, and the concept of a steel scrap threshold price is proposed. According to the analysis results, when the steel scrap unit price exceeds the steel scrap threshold price, an increase in the iron/steel ratio can reduce the production cost, and vice versa. When the gap between the steel scrap unit price and the steel scrap threshold price is relatively large, the impact of the iron/steel ratio on the production cost is more prominent. According to the calculation example, when steel production is fixed (284 358 t/month) and the steel scrap unit price is 263.2 yuan/t more than the steel scrap threshold price, an increase of 0.01 in the iron/steel ratio causes a monthly production cost reduction of approximately 750 000 yuan (2.63 yuan/t). When the amount of molten iron is fixed (270 425 t/month) and the steel scrap unit price is 140.7 yuan/t more than the threshold price, an increase of 0.01 in the iron/steel ratio causes a monthly production cost reduction of approximately 430 000 yuan (1.5 yuan/t). The results indicate that iron and steel enterprise should adjust the production strategy in time when the scrap price fluctuates, and then the production cost will be reduced.

Key words: iron/steel ratio; material flow; energy flow; model of production cost; steel scrap threshold price
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The steel production process is a dynamic process. The physical nature of its operation involves dynamic and orderly material flow in a "process network" under the driving force of energy flow, which proceeds according to a predefined "program" to achieve multi-objective optimization[1]. Therefore, material flow and energy flow are two major factors that affect the operations of a steel manufacturer. Currently, studies of material flow and energy flow focus on two aspects. The first one is from the perspective of a time and space relationship between material flow and energy flow. For example, Yin et al.[1-5] elaborated the steel manufacturer's operational nature and proposed that Chinese steel manufacturers should enter a new phase that is characterized by the setup of an energy flow network and energy control center. The second one is from the perspective of the material flow structure. For example, Lu et al.[6] examined the impact of the material flow structure on the total energy consumption and proposed some important concepts, such as a reference material flow diagram and a steel ratio coefficient. The iron/steel ratio is the most critical material flow structure parameter for descriptions of before ironmaking (BIM) and after steelmaking (SM). Recently, many researchers have conducted related studies. Huang et al.[7-11] carried out research in depth on scrap steel from a view of environmental and economic sustainable development.

This paper outlines the production cost and establishes a mathematical model on the basis of a standard material flow diagram[6]. The impact of the iron/steel ratio on the production cost is obtained by model analysis when the BIM total cost and the steel scrap unit price change. The concept of a steel scrap threshold price is proposed and verified by examples.

1 Model of Manufacturer's Production Cost

A manufacturer's production cost primarily includes the direct material cost, the direct labor cost and the manufacturing cost. The direct material cost includes the cost of raw material, auxiliary material and the cost of fuel and power; the direct labor cost includes the wages and benefits of workers; and the manufacturing cost includes the wages and benefits of management personnel. The direct material cost accounts for more than 75% of a manufacturer's production cost[11]. This cost can be divided into two categories: the material flow cost and the energy flow cost. The direct labor cost and the manufacturing cost remain constant within a statistical cycle. When the output capacity increases, the unit cost decreases, which is consistent with the marginal effect in economics. In this paper, the change in unit cost is defined as the marginal cost. Since the unit price of steel scrap can vary, a reasonable iron/steel ratio should be established to

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achieve the lowest cost.

1.1 Scope of study

The cost of a BIM system is considered as a whole in the raw material cost, which is referred to as the BIM total cost, including the material flow cost, energy flow cost, and marginal cost of the BIM system. The scope of this study is represented by the area enclosed by dotted line in Fig. 1. Here, CC, HR, CR, and SS represent continuous casting, hot rolling, cold rolling, and scrap steel, respectively.

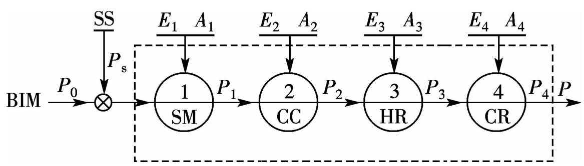

Fig. 1 Scope of system study

In Fig. 1, P_0 is the addition of molten iron, t; P_s is the steel scrap addition, t; E_i is the total energy consumption of the i-th process, tce (ton coal equivalent); A_i is the auxiliary material total consumption of the i-th process, t; P_i is the production of the i-th process, t; P is the gross output of steel, t.

Fig. 1 indicates that the material flow consists of the molten iron, steel scrap and auxiliary material that enter each process and that the energy flow consists of the energy that enters each process. Therefore, the material flow cost is the sum of the BIM total cost, the steel scrap cost and the process auxiliary material cost. The energy flow cost is the sum of the energy cost for each process. To construct the model of the production cost in this paper, the following assumptions are made:

1) In the CC, HR and CR processes, the auxiliary material cost is not counted, i. e., $A_2 = A_3 = A_4 = 0$, and the auxiliary material in the SM process is determined by the amount of molten iron.

2) The recycled material consumed in each process serves as an internal accounting index and is not included in the cost.

3) The relationship between the raw material flow and the product flow in each process can be represented by the product resource utilization, the material yield and the product yield.

4) A steel manufacturer's material flow and energy flow have a very strong coupling relationship[12]; a significant change in energy flow occurs after the change in material flow. Their relationship can be obtained by a regression method.

1.2 Establishment of model

This paper establishes a model of material flow cost, in which the energy flow cost is obtained based on a coupling relationship between the material flow and the energy flow. This cost is combined with the marginal cost to obtain the production cost.

1.2.1 Model of material flow cost

As previously described, the output of each process in Fig. 1 has the following relationships:

$$P_1 = P_0\eta_1 + P_s\alpha_s = (P_0 + P_s)\alpha_s \tag{1}$$

$$P_2 = P_1\eta_2 \tag{2}$$

$$P_3 = P_2\eta_3 \tag{3}$$

$$P_4 = P_3\eta_4 \tag{4}$$

where η_i is the total production efficiency of the i-th process; α_s is the steel scrap yield, %. When $i = 1$, $\eta_i = \alpha_s$.

Based on the definition of the iron/steel ratio[6], the amount of steel scrap can be obtained after processing:

$$P_s = \frac{P_1 - P_1 k_{ir}\alpha_s}{\alpha_s} \tag{5}$$

The steel scrap cost is calculated as

$$c_s = \frac{C_s P_s}{P_1} = \frac{(1 - k_{ir}\alpha_s) C_s}{\alpha_s} \tag{6}$$

where C_s is the steel scrap unit price, yuan/t; c_s is the steel scrap production cost yuan/t; k_{ir} is the iron/steel ratio.

The amount of molten iron is calculated as

$$P_0 = P_1 k_{ir} \tag{7}$$

The molten iron cost is

$$c_0 = \frac{C_0 P_0}{P_1} = k_{ir} C_0 \tag{8}$$

where C_0 is the material unit price, yuan/t; c_0 is the material production cost, yuan/t.

During the production process, the purpose of the auxiliary material is to remove impurities and provide cooling. Its amount is determined by the upstream process output. The amount of auxiliary material is obtained as

$$a_i = \frac{A_i}{P_1} = \frac{\alpha_i P_{i-1}}{P_1} \tag{9}$$

where A_i is the auxiliary material total consumption of the i-th process, t; α_i is the auxiliary material consumption rate of the i-th process, %; a_i is the ratio of the auxiliary material consumption of the i-th process to steel production.

The auxiliary material cost only exists in the steelmaking process, and its major function is to remove phosphorus, sulfur and silicon from molten iron. Therefore, Eq. (9) can be expressed as

$$a_1 = \frac{A_1}{P_1} = \frac{\alpha_1 P_0}{P_1} = \alpha_1 k_{ir} \tag{10}$$

The auxiliary material cost is

$$c_a = \frac{C_a \alpha_1 P_0}{P_1} = C_a \alpha_1 k_{ir} \tag{11}$$

where C_a is the auxiliary material unit price, yuan/t; c_a is the auxiliary material production cost, yuan/t.

The material flow production cost is

$$c_{\mathrm{m}}=\frac{(1-k_{\mathrm{ir}}\alpha_{\mathrm{s}})C_{\mathrm{s}}}{\alpha_{\mathrm{s}}}+k_{\mathrm{ir}}C_0+C_{\mathrm{a}}\alpha_1 k_{\mathrm{ir}} \tag{12}$$

where c_{m} is the material flow production cost, yuan/t.

1.2.2 Model of energy flow cost

From the concepts of energy consumption in a process and the steel ratio coefficient[8], the product of the two concepts is the energy consumption multiplied by the energy unit price, that is, the energy cost. The sum of the energy cost for each process is the total energy cost, i. e.,

$$c_{\mathrm{e}}=\sum_i(e_ip_i)C_{\mathrm{e}}=\sum_i(f_i(P_i)p_i)C_{\mathrm{e}} \tag{13}$$

where C_{e} is the energy unit price, yuan/t; c_{e} is the energy production cost, yuan/t.

There is a strong correlation between energy intensity of a process and its output through practical investigation. In this paper, a unary linear regression method is used to obtain the coupling relationship, i. e., $e_i=f_i(P_i)=m_iP_i+n_i$. Combining with Eqs. (1) to (4), we obtain $p_1=1$, $p_2=\eta_2$, $p_3=\eta_2\eta_3$, $p_4=\eta_2\eta_3\eta_4$. Eq. (13) can be expanded and simplified as

$$c_{\mathrm{e}}=((m_1P_1+n_1)+(m_2P_1\eta_2+n_2)\eta_2+(m_3P_1\eta_2\eta_3+n_3)\eta_2\eta_3+(m_4P_1\eta_2\eta_3\eta_4+n_4)\eta_2\eta_3\eta_4)C_{\mathrm{e}} \tag{14}$$

1.2.3 Model of marginal cost

The marginal cost is the ratio of the sum of the assets depreciation and the personnel benefits to steel production, i. e.,

$$c_{\mathrm{b}}=\frac{K}{P_1} \tag{15}$$

where c_{b} is the marginal production cost, yuan/t; K is the fixed cost, billion yuan.

1.2.4 Model of manufacturer's production cost

A manufacturer's production cost consists of the material flow cost, the energy flow cost and the marginal cost, i. e.,

$$c_{\mathrm{t}}=\frac{(1-k_{\mathrm{ir}}\alpha_{\mathrm{s}})C_{\mathrm{s}}}{\alpha_{\mathrm{s}}}+k_{\mathrm{ir}}C_0+C_{\mathrm{a}}\alpha_1k_{\mathrm{ir}}+((m_1P_1+n_1)+(m_2P_1\eta_2+n_2)\eta_2+(m_3P_1\eta_2\eta_3+n_3)\eta_2\eta_3+(m_4P_1\eta_2\eta_3\eta_4+n_4)\eta_2\eta_3\eta_4)C_{\mathrm{e}}+\frac{K}{P_1} \tag{16}$$

2 Model Analysis

Eq. (16) has two independent variables. First, when the iron/steel ratio and the steel production are independent variables, the variation in the iron/steel ratio is determined by the amount of molten iron and the steel production is fixed. Secondly, when the iron/steel ratio and the amount of molten iron are independent variables, the variation in the iron/steel ratio is determined by the steel production and the amount of molten iron is fixed.

2.1 The varying pattern in fixed steel production

When the steel production is fixed, we obtain the partial derivative of Eq. (16) with respect to the iron/steel ratio, i. e.,

$$\frac{\partial c_{\mathrm{t}}}{\partial k_{\mathrm{ir}}}=\frac{-\eta_1C_{\mathrm{s}}}{\alpha_{\mathrm{s}}}+C_0+C_{\mathrm{a}}\alpha_1 \tag{17}$$

When $C_{\mathrm{s}}<\alpha_{\mathrm{s}}(C_0+C_{\mathrm{a}}\alpha_1)/\eta_1$, $\partial c_{\mathrm{t}}/\partial k_{\mathrm{ir}}>0$. This finding indicates that the production cost has a positive correlation with the iron/steel ratio. Meanwhile, the steel scrap unit price diminishes and reducing the iron/steel ratio causes a decrease in the production cost, which increases the amount of steel scrap and reduces the amount of molten iron. When $C_{\mathrm{s}}>\alpha_{\mathrm{s}}(C_0+C_{\mathrm{a}}\alpha_1)/\eta_1$, $\partial c_{\mathrm{t}}/\partial k_{\mathrm{ir}}<0$. This finding indicates that the production cost has a negative correlation with the iron/steel ratio. Meanwhile, the steel scrap unit price increases and increasing the iron/steel ratio causes a reduction in the production cost, which reduces the amount of steel scrap and increases the amount of molten iron. When $C_{\mathrm{s}}=\alpha_{\mathrm{s}}(C_0+C_0\alpha_1)/\eta_1$, $\partial c_{\mathrm{t}}/\partial k_{\mathrm{ir}}=0$. Meanwhile, the production cost does not vary with the iron/steel ratio.

2.2 The varying pattern in fixed molten iron

When the amount of molten iron is fixed, we substitute $P_1=P_0/k_{\mathrm{ir}}$ into Eq. (16) to obtain the model of a manufacturer's production cost, i. e.,

$$c_{\mathrm{t}}=\frac{(1-k_{\mathrm{ir}}\eta_1)C_{\mathrm{s}}}{\alpha_{\mathrm{s}}}+k_{\mathrm{ir}}C_0+C_{\mathrm{a}}\alpha_1k_{\mathrm{ir}}+\left(\left(\frac{m_1P_0}{k_{\mathrm{ir}}}+n_1\right)+\left(\frac{m_2P_0\eta_2}{k_{\mathrm{ir}}}+n_2\right)\eta_2+\left(\frac{m_3P_0\eta_2\eta_3}{k_{\mathrm{ir}}}+n_3\right)\eta_2\eta_3+\left(\frac{m_4P_0\eta_2\eta_3\eta_4}{k_{\mathrm{ir}}}+n_4\right)\eta_2\eta_3\eta_4\right)C_{\mathrm{e}} \tag{18}$$

We obtain the partial derivative of Eq. (18) with respect to the iron/steel ratio, i. e.,

$$\frac{\partial c_{\mathrm{t}}}{\partial k_{\mathrm{ir}}}=\frac{-\eta_1C_{\mathrm{s}}}{\alpha_{\mathrm{s}}}+C_0+C_{\mathrm{a}}\alpha_1+\frac{(-m_1P_0-m_2P_0\eta_2^2-m_3P_0\eta_2^2\eta_3^2-m_4P_0\eta_2^2\eta_3^2\eta_4^2)C_{\mathrm{e}}}{k_{\mathrm{ir}}^2}+\frac{K}{P_0} \tag{19}$$

Eq. (19) indicates that the varying pattern of the production cost and the iron/steel ratio is determined by various factors, such as the iron/steel ratio, the amount of molten iron, the material and energy flow cost, and the resource utilization. Let $X=\alpha_{\mathrm{s}}(C_0+C_{\mathrm{a}}\alpha_1+(-m_1P_0-m_2P_0\eta_2^2-m_3P_0\eta_2^2\eta_3^2-m_4P_0\eta_2^2\eta_3^2\eta_4^2)C_{\mathrm{e}}/k_{\mathrm{ir}}^2+K/P_0)/\eta_1$. According to further analysis, when $C_{\mathrm{s}}<X$, the production cost has a positive correlation with the iron/steel ratio; when $C_{\mathrm{s}}>X$, the production cost has a negative correlation with the iron/steel ratio; and when $C_{\mathrm{s}}=X$, the production cost does not vary with the iron/steel ratio.

In the two previously described situations, a steel scrap unit price renders a manufacturer's production cost insensitive to the iron/steel ratio. When the steel scrap unit price exceeds this price, increasing the iron/steel ratio can result in a lower production cost. To achieve a higher steel scrap unit price, more molten iron and less steel scrap should be used. When the steel scrap unit price falls below this price, reducing the iron/steel ratio can result in a lower production cost. To achieve a lower steel scrap unit price, less molten iron and more steel scrap should be utilized under the premise that the requirement of the converter steelmaking production process is satisfied. This steel scrap unit price under the BIM total cost is defined as the steel scrap threshold price.

3 Case Studies

The data source for this case study consists of the monthly average data of one manufacturer in 2013. The discussion focused on the BIM total cost and the steel scrap unit price, which have a significant impact on the production cost; other parameters are set to be market and manufacturer's average values. The details are shown in Tab. 1.

Tab. 1 Relevant parameters of the model

Parameters	Value	Parameters	Value
η_1/%	90	m_4	−0.43
η_2/%	95	n_1	3.14
η_3/%	97	n_2	21.33
η_4/%	98	n_3	78.49
α_s/%	90	n_4	89.5
α_1/%	0.03	$K/10^8$ yuan	12
C_a/(yuan · t^{-1})	460	P_1/(t · month^{-1})	284 358
C_e/(yuan · t^{-1})	800	P_0/(t · month^{-1})	270 425
m_1	−0.25	C_s/(yuan · t^{-1})	&
m_2	−0.37	C_0/(yuan · t^{-1})	&
m_3	−2.17	k_{ir}	&

Note: & represents the parameter required for the discussion of the rule.

3.1 The varying pattern in fixed steel production

The BIM total cost of 2 860 yuan/t is used as an example to discuss the variation rule of the production cost vs. the iron/steel ratio. Fig. 2 indicates the variation rule of the production cost vs. the iron/steel ratio for different steel scrap unit prices in the case of fixed steel production. When the steel scrap unit price is 2 874 yuan/t, the production cost does not vary with the iron/steel ratio, i. e. , this price is the steel scrap threshold price for the BIM total cost of 2 860 yuan/t in the case of fixed steel production. When the steel scrap unit price exceeds 2 874 yuan/t, the production cost decreases with the increase in the iron/steel ratio. The more the steel scrap unit price exceeds 2 874 yuan/t, the higher the degree of negative correlation between the production cost and the iron/steel ratio. This finding indicates that the steel scrap utilization should be decreased and the molten iron utilization should be increased. When the steel scrap unit price falls below 2 874 yuan/t, the production cost increases with the increase in the iron/steel ratio. The more the steel scrap unit price falls below 2 874 yuan/t, the higher the degree of positive correlation between the production cost and the iron/steel ratio. This finding reveals that the steel scrap utilization should be increased and the molten iron utilization should be decreased under the premise that the requirement of the converter steelmaking production process is satisfied (The minimum iron/steel ratio is 0.8). With different BIM total cost values, the same conclusion can be obtained, with the exception that the steel scrap threshold price is slightly different.

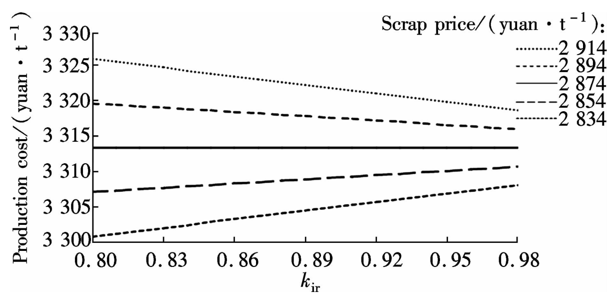

Fig. 2 The varying pattern in fixed steel production

3.2 The varying pattern in fixed molten iron

The BIM total cost of 2 860 yuan/t is used as an example to facilitate a discussion on the variation rule of the production cost vs. the iron/steel ratio. Fig. 3 indicates the variation rule of the production cost vs. the iron/steel ratio for different steel scrap unit prices in the case of a fixed amount of molten iron. When the steel scrap unit price is 2 996 yuan/t, the production cost exhibits a nonlinear relationship with the iron/steel ratio. In the case of the converter steelmaking process, the fluctuation in production cost is less than 0.03%. Thus, the results indicate that the production cost does not vary with the iron/steel ratio at this steel scrap unit price, that is, this price is the steel scrap threshold price for the molten iron total cost of 2 860 yuan/t in the case of a fixed amount of molten iron. When the steel scrap unit price exceeds 2 996 yuan/t, the production cost has a negative correlation with the iron/steel ratio. The larger the discrepancy, the smaller the amount of steel scrap and the larger the amount of molten iron that are to be used. When the steel scrap unit price is less than 2 996 yuan/t, the production cost has a positive correlation with the iron/steel ratio. A

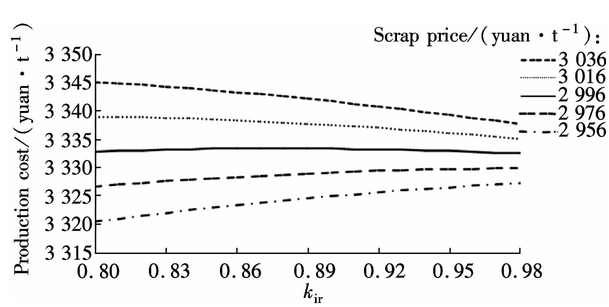

Fig. 3 The varying pattern in fixed molten iron

larger discrepancy requires that more steel scrap and less molten iron should be used. The same conclusion can be obtained with different BIM total cost values, with the exception of slightly different steel scrap threshold prices.

The steel scrap unit price (3 137 yuan/t) is used as an example for the calculations in the case of fixed steel production (284 358 t/month). An increase of 0.01 in the iron/steel ratio causes a monthly reduction of approximately 750 000 yuan in the production cost (2.63 yuan/t). In the case of a fixed amount of molten iron (270 425 t/month), an increase of 0.01 in the iron/steel ratio produces a monthly reduction of approximately 430 000 yuan in the production cost (1.5 yuan/t).

4 Conclusion

This paper establishes a model of the production cost. The concept of a steel scrap threshold price is proposed. When the steel scrap unit price in the market exceeds the steel scrap threshold price, an increase in the iron/steel ratio causes a reduced production cost, and vice versa.

Based on actual data for the case of fixed steel production (284 358 t/month), an increase of 0.01 in the iron/steel ratio produces a monthly reduction of approximately 750 000 yuan in production cost (2.63 yuan/t) when the steel scrap unit price exceeds the steel scrap threshold price by 263.2 yuan/t (The current steel scrap threshold price is 2 874 yuan/t). In the case of a fixed amount of molten iron (270 425 t/month), an increase of 0.01 in the iron/steel ratio produces a monthly reduction of approximately 430 000 yuan in production cost (1.5 yuan/t) when the steel scrap unit price exceeds the threshold price by 140.7 yuan/t (The current steel scrap threshold price is 2 996 yuan/t).

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基于物流能流变化的铁钢比对生产成本的影响

陆　彪[1]　陈　光[2]　陈德敏[2]　虞维平[1]　丁　毅[3]

([1] 东南大学能源与环境学院,南京 210096)

([2] 安徽工业大学建筑工程学院,马鞍山 243032)

([3] 马鞍山钢铁股份有限公司,马鞍山 243000)

摘要:建立了钢铁企业生产成本模型,分别讨论了钢产量不变和铁水量不变的 2 种情况下,生产成本随铁钢比的变化规律,并提出废钢临界价格概念.分析表明,当废钢单价高于废钢临界价格时,增加铁钢比可以降低生产成本,否则相反.废钢单价与废钢临界价格相差较大时,铁钢比对生产成本的影响更显著.实例计算表明,当钢产量不变(284 358 t/月),废钢单价高于废钢临界价格 263.2 元/t 时,铁钢比增加 0.01,每月可降低生产成本 75 万元左右(2.63 元/t);当铁水量不变(270 425t/月),废钢单价高于临界价格 140.7 元/t 时,铁钢比增加 0.01,每月可降低生产成本 43 万元左右(1.5 元/t).结果表明,钢铁企业应根据废钢单价的波动情况及时调整生产策略,以降低生产成本.

关键词:铁钢比;物流;能流;生产成本模型;废钢临界价格

中图分类号:TK-9