INTRODUCTION

Steel has remained the most crucial of all structural materials. However, the steel production processes have changed over the years. Currently, due to the tendency of eliminating high energy consuming technologies, in both the international and domestic steel industry, liquid steel is manufactured in two basic aggregates: oxygen-blown converters and electric arc furnaces [1]. The development of technique and technology in the scope of steel production in an arc furnace is aimed at improving the efficiency of the installations used, increasing the quality of steel and reducing the production costs.

The basic iron-bearing medium for EAF is steel scrap. Strong competition requires efficient utilisation of raw materials, especially secondary raw materials like steel scrap. Bearing in mind the contemporary tendencies to implement and develop technologies contributing to protection of natural resources and environment, including those reducing the carbon dioxide emission, an EAF as a scrap-based steel melting aggregate is a particularly attractive solution. Steel smelting in an electric furnace enables steel recycling, which can be stressed as its great environmental advantage [2]. In light of the market economy requirements and strong competition in the global market, the fact of undertaking various subjects in the field of economic optimisation of steel production seems completely justified. The presented paper constitutes an analysis of the example of application of the multi-criteria optimisation method to improve efficiency of steel smelting in an electric arc furnace (EAF) through appropriate choice of the charge scrap. A measurable effect of applying such a methodology of choosing the metal charge is the ability to reduce the unit cost of steel smelting.

Key words: EAF, multi-criteria optimisation, charge scrap, crude steel

OPTIMISATION AND CHOICE OF A CRITERION

The contemporary economy is characterised by an increase in the number of manufacturers of identical products competing with one another. The same phenomenon can be noticed in the steel industry and it occurs in all stages of the final product manufacture. In practice, there is usually a problem: a solution of optimisation task covering two functions: achievement of a maximum effect (e.g. yield of crude steel) on simultaneous minimisation of expenditures. Such problems are considered to function under the class of multi-criteria optimisation models the most common of which are two-criteria problems. The examinations in question were performed at an electric steel-smelting shop assuming a quotient programming model [3,4] being one
of the methods of finding compromising solutions under the tasks of multi-criteria optimisation with two contradictory functions.

Two constituents comprise an overall product cost: constant cost and variable cost. Only the variable cost can be altered during current production. The relevant calculations imply that the share of variable cost in the overall cost of steel smelting in EAFs is 75 – 85 %, therefore, from the perspective of the steel production optimisation process for an electric furnace, one of the most significant criteria is the minimisation of the production cost variable constituent.

Based on the cause and effect analysis (diagram by Ishikawa) conducted [5], a block diagram was prepared for the variable cost components for crude steel smelted in the EAF – Figure 1.

The Pareto-Lorenz analysis conducted showed that two cost components, namely the metal charge costs and the electric power costs, out of all crude steel production variable cost components (metal charge, electric power, graphite electrodes, sag-forming additives, mould powders, auxiliary materials, refractory materials, technological oxygen, natural gas, technical gases), accounted for more than 85 % including the scrap material cost of ca. 70 % [5,6]. Therefore, one of the optimisation criteria chosen was the minimisation of the production cost variable constituent.

Based on the cause and effect analysis (diagram by Ishikawa) conducted [5], a block diagram was prepared for the variable cost components for crude steel smelted in the EAF – Figure 1.

EXAMINATIONS

The examinations were conducted at a steel-smelting shop equipped with an UHP electric arc furnace with eccentric bottom tapping (EBT) manufactured by Mannesmann Demag. The variables assumed for the steel manufacture in the EAF were the masses of the individual sorts of charge materials. A problem of quotient programming with a hyperbolic objective function was established to find a compromise solution in which one of the functions was to be the cost minimisation and the other – maximisation of the metal yield from scrap.

The quotient programming task model is composed of limiting conditions in a linear form, boundary conditions as well as objective functions in a fractional form [7].

The objective function was established as follows:

$$F(X) = \frac{\sum_{j=1}^{n} c_j \cdot X_j}{\sum_{j=1}^{n} d_j \cdot X_j} \rightarrow \min$$

where:

$$c_j$$ – unit cost of scrap material (for $$j = 1,2,...,n$$ scrap sorts),

$$d_j$$ – yield of scrap mass (for $$j = 1,2,...,n$$ scrap sorts),

$$X_j$$ – share of steel scrap in the charge burden (for $$j = 1,2,...,n$$ scrap sorts; $$X_1 + X_2 + ... + X_n = 1$$).

An additional limitation was the non-negativeness of decisive variables. In the example being analysed, the following optimum values must be obtained:

$$F_1(X) = \sum_{j=1}^{n} d_j \cdot X_j \rightarrow \max$$

$$F_2(X) = \sum_{j=1}^{n} c_j \cdot X_j \rightarrow \min$$

The solution to such a problem is an attempt to find a certain compromise, since it is impossible to come to a solution enabling that criterion $$F_1$$ (yield of crude steel from the charge scrap) reaches its maximum, and criterion $$F_2$$ (cost of charge scrap) reaches its minimum.

While creating a mathematical model the task of which is to optimise the metal charge material for EAF, one must identify the classification of the charge scrap being applied. It is very diverse and depends on the grades of steel manufactured and the sorts of charge scrap available commercially in the market [8,9]. The following properties should be entailed for the sake of the scrap material classification:

– content of alloying elements possible to be reclaimed in the steel smelting process;
– content of harmful elements (including sulphur, phosphorus, copper, zinc) and undesirable elements (e.g. chromium, nickel, molybdenum, tin);
– geometry of scrap (mass density and scrap size) – the knowledge of the scrap material geometry enables optimum filling of the EAF charge baskets.

In terms of the scrap material origin, one can speak of home scrap and outside scrap (scrap from fully depreciated machines, tools). Within the last twenty five
years, the share of post-depreciation scrap in use has risen considerably due to the development of the continuous casting technology and the increase in manufacture of steel-containing products replaced by users with new ones (e.g. cars, household appliances) [9, 10]. However, due to the large share of outside scrap in the overall mass of charge materials, its quality drops, which particularly to the increase of the content of undesirable elements and copper.

The classification of scrap assumed in the case being analysed was the one applied in the electric steel smelting shop entailing the individual sorts (Table 1) without the home scrap due to the impossibility of determining its price.

Table 1 Metal charge scrap classification (scrap sorts)

<table>
<thead>
<tr>
<th>Scrap (independent variable)</th>
<th>Bulk density / Mg·m⁻³</th>
<th>Dimensions max. / mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light scrap</td>
<td>X₁ &lt; 0.6</td>
<td>1 000 x 500 x 500</td>
</tr>
<tr>
<td>Medium-weight scrap</td>
<td>X₂ 0.6 – 0.7</td>
<td>1 200 x 500 x 500</td>
</tr>
<tr>
<td>Heavy scrap</td>
<td>X₃ &gt; 0.7</td>
<td>1 200 x 500 x 500</td>
</tr>
<tr>
<td>Scrap in package</td>
<td>X₄ to 1.0</td>
<td>1 000 x 500 x 500</td>
</tr>
<tr>
<td>Pressed steel chips</td>
<td>X₅ 0.6 – 0.8</td>
<td>50 - 150</td>
</tr>
<tr>
<td>Special scrap (Cu &lt; 0.15 %)</td>
<td>X₆ &gt; 0.7</td>
<td>1 200 x 500 x 500</td>
</tr>
</tbody>
</table>

Since the purpose of the mathematical model being developed was to find a compromising solution between minimisation of the charge scrap cost and maximisation of the metal yield from this scrap, in the first instance, both the metal yield from the individual sorts of scrap material (crude steel mass) and the scrap material prices needed to be estimated. In order to estimate the mass of crude steel, data from 3 638 melts were used after the initial selection by the 3S method [11] (assuming that the variables are subject to normal distribution), and on such a basis, a specific dependence in the form of a multiple regression equation was established to enable programming of the crude steel yield depending on the composition of the metal scrap. Table 2 contains a collation of the metal yield ratios obtained for the individual sorts of scrap material as well as the price relations between these sorts.

The problem of quotient programming with an objective function (1) entailed the limiting conditions related to the scrap material geometry (optimum filling of charge baskets and time required to melt the heavy scrap) as well as the technological conditions applicable in the steel smelting shop (assuming that the charge was loaded into the EAF with two charge baskets):
- on the bottom of both charge baskets, there should be light scrap in the quantity not exceeding 15 %
- on the bottom of both charge baskets, this is about 32 % of the charge scrap mass:

- the mass of heavy scrap including the special scrap should not exceed 40% of the overall charge scrap mass, and its minimum share should not be smaller than 20 %:

\[ 0.20 \leq X₃ + X₆ \leq 0.40 \]

- the mass of packed scrap should not exceed 5 % of the charge scrap mass:

\[ X₆ \leq 0.05 \]

Based on dependence (2) and (3), the objective function in the optimisation problem being analysed assumes the following form (data in Table 2):

\[ F(X) = c(X₁ + 1.385 \cdot X₂ + 1.175 \cdot X₃ + 0.8135 \cdot X₄ + 0.8646 \cdot X₅ + 0.9143 \cdot X₆ + 0.8327 \cdot X₇ + 0.9253 \cdot X₈) \rightarrow \text{min} \]  

The metal charge was chosen for the following grades of steel:
- for the grades most commonly manufactured at the steelworks examined (normal quality structural steel – without special scrap) – set I,
- for the steel of copper content below 0.35 % – set II,
- for the charge scrap without packed scrap – set III.

The shares of the individual grades of steel obtained as well as the values of the objective function, the assumed yield of crude steel from metal charge and its prices have been provided in Table 3.
The calculations performed imply that under the conditions present at the steel smelting shop examined, entailing the limiting conditions, the minimum price of metal charge on maximum yield of crude steel from scrap can be attained if the charge material is composed of 32% of light scrap, 38% of medium-weight scrap, 5% of pressed steel chips and packed scrap respectively and 20% of special scrap. Such a composition of the metal charge can be used for smelting of both standard structural steel and the steel with copper content not exceeding 0.35% of Cu. The share of packed scrap exerts an influence on the price reduction, whereas the share of special scrap may increase the yield of crude steel. If in set I, the heavy scrap is replaced with special scrap, then the yield of crude steel will come to 0.857863, and the price of 1 Mg of scrap will equal 1.29605 \( c \) of the light scrap. Consequently, the share of special scrap in the charge material exerts a positive influence on the yield of crude steel from scrap material, and at the same time, it does not cause a significant increase in the price of the charge material (assuming the share of special scrap on the level of 20%).

CONCLUSIONS

It is the market economy that requires the criterion of production optimisation to remain in the economic domain, and in most cases, it can be the variable cost of the product manufactured. Striving to solve such optimisation tasks, as e.g. attaining the maximum yield of crude steel from metal scrap on minimum steel scrap costs, it is reasonable to find a compromising solution by applying the quotient programming method with a hyperbolic objective function. An additional advantage resulting from application of mathematical, multi-criteria optimisation models is the possibility of using common spreadsheets featuring the basic tools of mathematical analysis.

The optimisation solution defined for the EAF charge material implies that under the conditions present at the electric steel smelting shop examined and assuming the aforementioned limiting conditions:

- the cost of 1 Mg of scrap in the EAF charge material should not exceed 1.3 of the price of 1 Mg of light scrap, and at the same time, it enables attaining the yield of crude steel on the level of 0.857 \( c \) ÷ 0.86,
- the metal charge optimisation under the conditions of the steelworks examined should lead to reduction of the price of 1 Mg of metal charge by ca. 0.15 \( c \) ÷ 0.52 of the price of 1 Mg of light scrap.

REFERENCES

[1] Lis T., Metalurgia stali o wysokiej czystości, Wyd. Pol. Śl., Gliwice, 2009

Note: The responsible for English language is P. Nowak, Katowice, Poland.

Table 3 Optimum composition of metal charge for EAF

<table>
<thead>
<tr>
<th>share in the charge scrap mass / %</th>
<th>Set I</th>
<th>Set II</th>
<th>Set III</th>
</tr>
</thead>
<tbody>
<tr>
<td>( X_1 )</td>
<td>0.32</td>
<td>0.32</td>
<td>0.32</td>
</tr>
<tr>
<td>( X_2 )</td>
<td>0.43</td>
<td>0.38</td>
<td>0.48</td>
</tr>
<tr>
<td>( X_3 )</td>
<td>0.20</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( X_4 )</td>
<td>0.05</td>
<td>0.05</td>
<td>0</td>
</tr>
<tr>
<td>( X_5 )</td>
<td>0</td>
<td>0.05</td>
<td>0</td>
</tr>
<tr>
<td>( X_6 )</td>
<td>0</td>
<td>0.20</td>
<td>0.2</td>
</tr>
<tr>
<td>( F(X) )</td>
<td>1.5114c</td>
<td>1.503318c</td>
<td>1.513271c</td>
</tr>
<tr>
<td>( F_1(X) )</td>
<td>0.857663</td>
<td>0.858268</td>
<td>0.860388</td>
</tr>
<tr>
<td>( F_2(X) )</td>
<td>1.29605c</td>
<td>1.29025c</td>
<td>1.302c</td>
</tr>
</tbody>
</table>