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SCRAP-INTENSIVE WROUGHT ALUMINUM ALLOYS OF STANDARD QUALITY

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Abstract

To remain competitive, wrought aluminum alloys should offer the customer improved mechanical properties, achieved through recycling. To ensure this, it is necessary to organize a scrap yard with different material streams, each with a proper and well-controlled chemical composition, and to develop the software for calculating the proper combination of material streams that is essential for achieving the required alloy composition. An algorithm was developed for calculating the optimum combination of material streams for providing the standard composition of the pre-melting mixture, the required mechanical properties of the alloy and the minimum cost of production within the entire processing chain. It does not favour in advance the formulation of alloys with an increased amount of scrap, but selects a solution based on the optimum cost of production. The algorithm is also useful for tailoring recycling-friendly compositions of wrought aluminum alloys and for optimizing the production technology.

Introduction

The improved global market position of competitive advanced materials, especially the ultra-high-strength steels (recently promoted as functionally lighter and cheaper than wrought aluminum alloys) will influence the future costs of wrought aluminum alloys significantly.

To remain competitive with advanced high-strength steels and other engineering materials, wrought aluminum alloys should offer the customer a favourable cost-performance ratio, or, in other words, enhanced mechanical properties ensured by cost-effective production. To achieve this goal, it is necessary to enhance the alloy's properties (especially the tensile strength), while at the same time minimizing the costs. The properties of wrought aluminum alloys are the result of a complex interaction between the chemical composition and the microstructural features obtained during the solidification, thermal treatments and deformation processing [1]. Thus, under constant processing parameters, the properties are a consequence of the chemical composition of the alloy, and, vice-versa, the tolerance limits for the concentration intervals of the alloying elements depend on the required properties. On the other hand, cost reduction mostly depends on the technological possibilities of replacing as many of the expensive raw materials (the primary aluminum and the alloying elements) as possible with scrap. The extent of such a replacement depends on the ability of the production technology to preserve the standard composition and quality of the alloy or, to put it another way, to meet customer requirements by offering scrap-intensive alloys. In other words, the difficulty in recycling wrought aluminum alloys is the problem of achieving the standard tolerances, or more generally, the ability of an alloy to absorb elements not normally present in its composition [2]. This is the starting point for designing the so-called "recycling-friendly wrought aluminum alloys".

To ensure more recycling of wrought aluminum alloys, it is necessary to organize the scrap yard [3, 4] so that it consists of different material streams, each with a proper and well-controlled chemical composition. In addition, it is necessary to develop the software for calculating the proper combination of material streams that is essential for achieving the required alloy composition – standard alloys or the alternative, so-called "recycling friendly alloys" [5].

In this work an algorithm for calculating the optimal combination of material streams for providing the standard composition of the pre-melting mixture, the required mechanical properties of the alloy and the minimum cost of production within the entire processing chain will be presented.

The description of the model

The model provides a procedure for: (i) selecting the proper material streams from those available in the scrap yard and (ii) calculating their shares in order to achieve the prescribed composition of the pre-melting mixture for the production of wrought aluminum alloys with a standard composition.

The individual material streams represent the fractions of aluminum scrap sorted from the incoming material to an exactly defined chemical composition, Fig. 1. In addition, as well as fractions of aluminum scrap, the model also involves material streams of alloying elements as well as the primary aluminum and the impurities. The compositions of the individual material streams are represented in the model by vectors, the components of which are concentrations (i.e., shares) of particular elements involved in the material streams. In this way, a vector with n components describes the composition of a material stream that consists of n different elements – among which are all the alloying elements, impurities and aluminum.

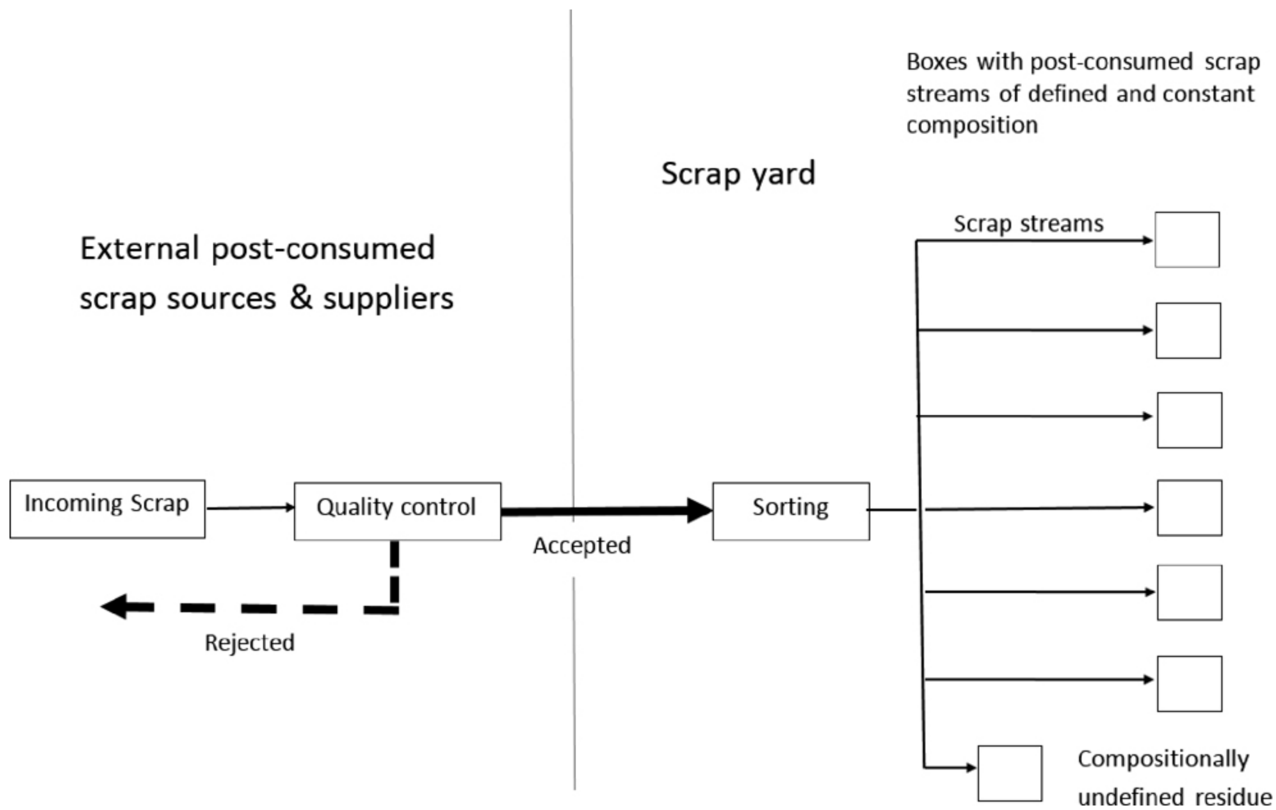

Fig. 1: Organization of the scrap yard for the recycling of wrought aluminum alloys from post-consumed scrap in accordance with the model

According to the model, the scrap yard consists of m different material streams. The compositions of all the material streams are written using a matrix of the material streams or, in the more developed form, using a matrix of the composition of the material streams. The shares of the individual elements are presented as intervals using technologically prescribed widths.

The unknowns calculated are the shares of the particular material streams that are necessary to achieve the proper composition of the pre-melting mixture of scrap and raw materials. The composition of the pre-melting mixture defined the vector with n components corresponding to the shares of the individual elements appearing in the stream. In addition, also in this case, the shares as the components of the vector are intervals, using the interval widths prescribed by the standard.

In addition to all the possible solutions (the shares of the various material streams), the algorithm searches for that particular solution which provides the minimum cost of the pre-melting mixture. To do this, it is necessary to introduce a matrix of the cost of the material streams and define the matrix of the cost of formation of the pre-melting mixture, in which the individual articles appear as the costs of each of the material streams. The unknown shares of the material streams calculated under the condition that the sum of the articles of the matrix of the cost of formation of pre-melting mixture is a minimum.

Definitions of the basic variables applied in the model

Matrix of material streams

The material streams existing in the scrap yard are described using the following matrix of the material streams:

$$\boldsymbol{R}_m = \begin{pmatrix} r_1 \\ \vdots \\ r_m \end{pmatrix}$$

(1)

The compositions of the individual material streams are described using a vector, the components of which represent the shares of particular elements appearing in the stream:

$$r_i = (x_{i1}, x_{i2}, x_{i3}, \ldots\ldots\ldots . x_{in}) \tag{2}$$

The index i corresponds to the i materials stream, while x_{ij} denotes the share of the element j (j = 1,2,3,…n) in the stream i (i = 1,2,3,… m).

Based on the above, the matrix of the material streams $\boldsymbol{R}_m$ can be transformed into the matrix of the composition of material streams $\boldsymbol{X}_{mn}$ in which the components of the matrix correspond to the shares of the chemical elements in the material streams:

$$R_m = X_{mn} = \begin{pmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{pmatrix} \tag{3}$$

Moreover, it is important to note that the sum of the shares inside an individual material stream i is always equal to 1:

$$\sum_{j=1}^{n} x_{ij} = 1 \tag{4}$$

Vector of the shares of the material streams

The components of this vector are the shares of the individual material streams, which are the main outputs calculated by the model:

$$A_m = (a_1, a_2, a, \ldots\ldots . a_n) \tag{5}$$

Vector of the chemical composition of the pre-melting mixture

This vector defines the chemical composition of the pre-melting mixture:

$$V_n = (v_1, v_2, v_3, \ldots\ldots . v_n) = \sum_{i=1}^{m} \sum_{j=1}^{n} a_i \cdot r_{ij} \tag{6}$$

Here, the symbols $v_1, v_2, v_3, \ldots\ldots . v_n$ represent the shares of the individual chemical elements appearing in the pre-melting mixture

Again, for the sums of the shares of the material streams and the chemical elements it is the case that:

$$\sum_{i=1}^{m} a_i = 1 \tag{7}$$

$$\sum_{i=1}^{n} v_i = 1 \tag{8}$$

Vector of the cost of the material streams

The components of this vector represent the costs of the individual material streams:

$$\boldsymbol{C}_m = (c_1, c_2, c_3, \ldots\ldots . c_n) \tag{9}$$

Finally, combining all the above-defined matrices, one can formulate the matrix of the cost of the production of the pre-melting mixture, $\boldsymbol{V}_m$:

$$\boldsymbol{V}_m = \boldsymbol{A}_m \cdot \boldsymbol{C}_m \cdot \boldsymbol{R}_{mn} = \begin{pmatrix} c_1 a_1 r_1 \\ \vdots \\ c_m a_m r_m \end{pmatrix} \tag{10}$$

It is important to note that the components of this matrix define the cost of the individual streams applied for the formation of the pre-melting mixture.

Correlation between the mechanical properties and the chemical composition of the wrought aluminum alloys

The mechanical properties of the wrought aluminum alloys processed in this model are the yield strength $\boldsymbol{YS}$, the tensile strength, $\boldsymbol{TS}$, the elongation $\boldsymbol{A}$ and the hardness $\boldsymbol{H}$.

In all cases considered in this study, the general assumption is made that under the constant conditions of the thermal treatments and the deformation processing, the mechanical properties of the alloy are functions of the chemical composition:

$$\boldsymbol{YS} = \boldsymbol{f_1}(\boldsymbol{v_1}, \boldsymbol{v_2}, \boldsymbol{v_3}, \dots \dots .., \boldsymbol{v_n}) \tag{11}$$

$$\boldsymbol{TS} = \boldsymbol{f_2}(\boldsymbol{v_1}, \boldsymbol{v_2}, \boldsymbol{v_3}, \dots \dots .., \boldsymbol{v_n}) \tag{12}$$

$$\boldsymbol{A} = \boldsymbol{f_3}(\boldsymbol{v_1}, \boldsymbol{v_2}, \boldsymbol{v_3}, \dots \dots .., \boldsymbol{v_n}) \tag{13}$$

$$\boldsymbol{H} = \boldsymbol{f_4}(\boldsymbol{v_1}, \boldsymbol{v_2}, \boldsymbol{v_3}, \dots \dots .., \boldsymbol{v_n}) \tag{14}$$

In practice, the functions $\boldsymbol{f_1}, \boldsymbol{f_2}, \boldsymbol{f_3}\ \boldsymbol{inf_4}$ are usually polynomial, with the unknowns being the shares of the alloying elements in the alloy $v_1, v_2, v_3, \dots \dots .., v_m$.

The shares of the alloying elements $v_1, v_2, v_3, \dots \dots .., v_m$ are presented as the intervals of the concentration:

$$v_i = \overline{v_i} \pm \Delta v_i \tag{15}$$

where $\overline{v_i}$ is the average value of the interval, and $2\Delta v_i$ is its width.

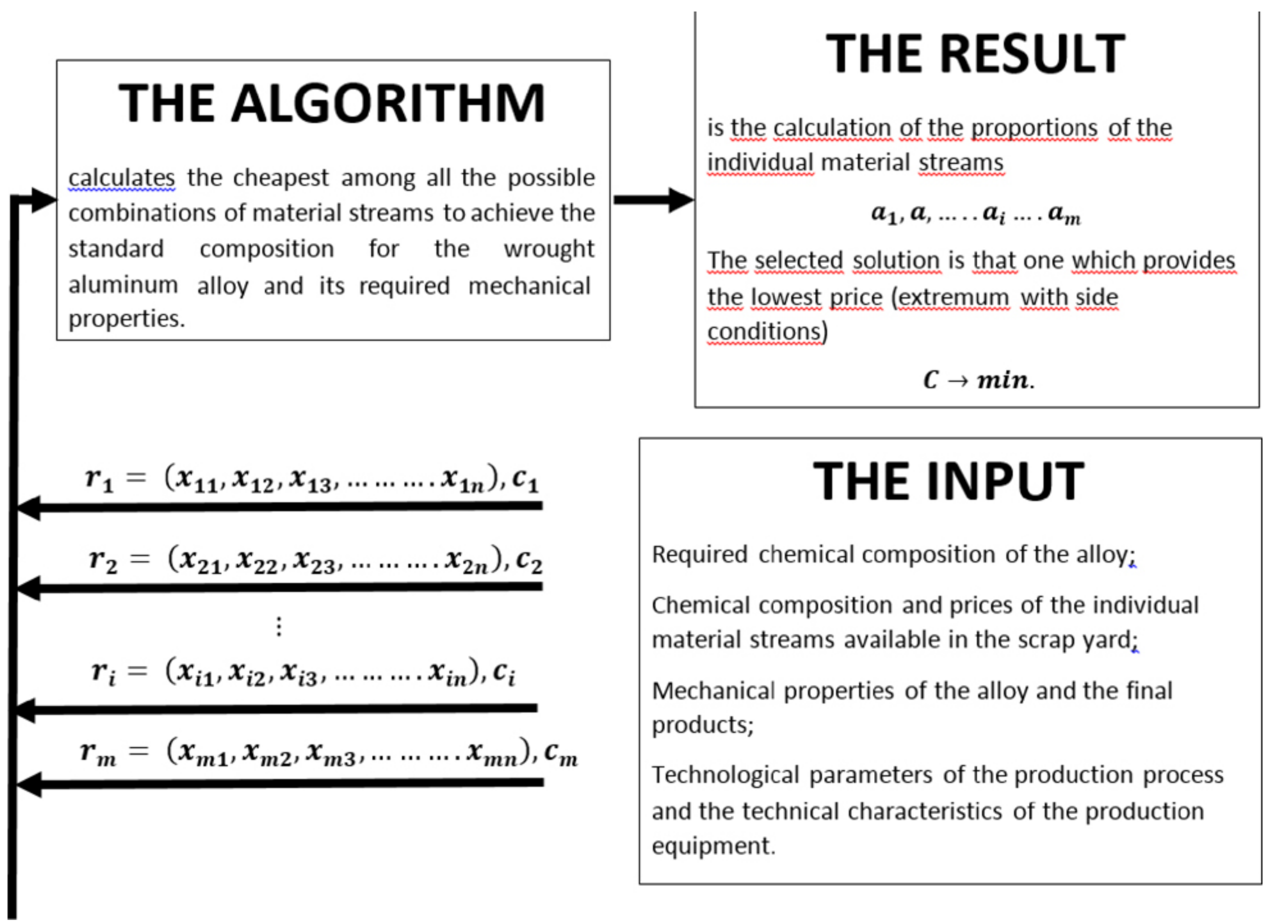

Fig. 2: Flowchart of the developed algorithm

Calculation of the shares of the material streams

The algorithm is looking for the cheapest combination of material streams to achieve the standard composition of the pre-melting mixture and the required mechanical properties in the alloy. The following data is used in the algorithm:

- The alloy chemical composition, prescribed by the vector of the pre-melting mixture, $V_n = (v_1, v_2, v_3, \dots\dots\dots v_n)$,

- The mechanical properties (yield strength $\boldsymbol{YS}$, tensile strength, $\boldsymbol{TS}$, elongation $\boldsymbol{A}$ and hardness $\boldsymbol{H}$),

- The number and the chemical compositions of the material streams, defined by the vectors of the individual material streams, $r_i = (x_{i1}, x_{i2}, x_{i3}, \dots\dots\dots\dots x_{in})$,

- The parameters of the technological process (thermal treatments, deformation processing),

- The technical characteristics of the production equipment (useful for the proper estimation of the total cost of the losses within the production chain).

The algorithm calculates the shares of the material streams, which are defined by the matrix of the shares of the material streams, $A_m = (a_1, a_2, a, \dots\dots\dots a_n)$ and among all possible solutions. In this way it is possible to achieve the proper composition and mechanical properties of the alloy, while selecting the solution with the lowest cost. With respect to all the costs applied in the algorithm, in addition to the costs of the materials, also the costs of the production and all the losses caused by using scrap are included. Fig. 2 presents the complete procedure for the calculation.

The difficulty is in the fact that theoretically there are an unlimited number of possible solutions or linear combinations by which it is possible to achieve the desired composition of the pre-melting mixture. Because of this, it is necessary to introduce the cost criterion, according to which there is only one cheapest combination, ensuring in that way the explicitness of the solution to the problem.

The base for the development of the algorithm is the previously formulated assumption that the properties of the wrought aluminum alloys are created by a complex interaction of the chemical composition and the microstructural features obtained during the solidification, the thermal treatments and the deformation processing. Consequently, from the mathematical point of view, the mechanical properties and the chemical composition of the wrought aluminum alloy cannot be independent variables. The mechanical properties are a consequence of the chemical composition of the alloy and vice-versa, while the tolerance limits of the intervals of the concentrations of alloying elements depend on the required mechanical properties. The problem is in the fact that these correlations between the chemical composition and the mechanical properties are not necessarily functional or bijective (based on a one-to-one correspondence, where every element of one set is paired with exactly one element of the other set), and not linear, which additionally aggravates the programing of the algorithm.

The vector of the pre-melting mixture, V_n, which defines with its components (shares of elements) the desired composition of the pre-melting mixture, can be written as a linear combination of the material streams, r_{ij}, where the coeficients of the linear combination appear as the shares of the individual material streams (unknowns determined by the model).

In industry, the number of material streams and their shares in the pre-melting mixture, m, which are unknowns, is usually higher than the number of alloying elements, n. Hence, in practice it is often the case that m>>n. Consequently, the number of unknowns in the system is higher than the number of equations and, therefore, the system has several possible solutions. In other words, the algorithm will recognize several possible ways of combining different streams (different solutions) in order to achieve the proper composition of the pre-melting mixture and the required mechanical properties of the alloy. Because of that, it is necessary to introduce the cost criterion, according to which there is only one cheapest combination, ensuring in this way the explicitness of the solution to the problem.

The optimum composition of the pre-melting mixture is defined by the shares $(a_1, a_2, \dots. a_m)$ calculated under the condition that the cost of the pre-melting mixture, $C(a_1, a_2, a_3, \dots\dots a_m)$, or in another words the sum of elements of the matrix $\boldsymbol{V}_m$, should be a minimum:

$$C(a_1, a_2, a_3, \dots\dots a_m) = \sum_{i=1}^{m} c_i a_i \rightarrow min. \tag{16}$$

The algorithm is looking for the minimum of the function $C(a_1, a_2, a_3, \dots\dots a_m)$ for more variables:

$$dC(a_1, a_2, a_3, \dots\dots a_m) = \sum_{i=1}^{m} \frac{\partial C}{\partial a_i} da_i = 0 \tag{17}$$

Results discussion

The algorithm developed in this work offers several advantages in tailoring a pre-melting mixture for the production of wrought aluminum alloys by combining the material streams of different sources of aluminum and alloying elements (old or new aluminum scrap, returning material, primary aluminum, pure alloying elements).

One of the important advantages is that the algorithm does not favour, in advance, the obtaining of alloys with an increased amount of scrap, but enables a decision-making procedure to achieve the best choice of constituents based on the resulting cost of the mixture. In other words, the algorithm will follow the requirements relating to the chemical composition and the mechanical properties and, based on that, defines the shares of the material streams from the digitalized stock of raw materials (primary aluminum and alloying elements) and different kinds of aluminum scrap, but in a way that will provide the minimum cost of production (within the entire production chain). In this way, the cost of production involves not only the cost of the raw materials and scrap, but also the cost of all the processing losses caused by an increased amount of scrap.

The algorithm also offers an option by which, based on the prescribed mechanical properties, it determines the proper chemical composition (the standard one, but, if necessary, a composition with narrower compositional tolerances) and after that computes the shares of the material streams from digitalized stock, again under the condition of the minimum cost of production.

The algorithm could also be applied in the opposite direction; therefore, in such a way as to correlate the changes in the concentrations of the alloying elements into the changes of the mechanical properties, enabling in this way the tailoring of the standard, but more recycling-friendly, compositions of the wrought aluminum alloys.

Finally, the algorithm, which correlates the incoming chemical composition and the processing parameters with the properties of the final products, could also be applied for the optimization of the production technology, especially the thermal treatments and the deformation processing as a way of achieving the desired alloy properties.

Conclusion

An algorithm was developed for organizing the scrap yard (grade, number and chemical composition of the individual material streams) involved in the production of wrought aluminium alloys. As the result, the standard composition of the pre-melting mixture, the required mechanical properties of the alloy and the minimum cost of production were computed. In addition, the algorithm was applied for tailoring recycling-friendly compositions of wrought aluminum alloys and for optimizing the production technology.

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