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UDC 621.746.6

DOI: 10.15587/2312-8372.2018.150585

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OPERATION OPTIMIZATION OF HOLDING FURNACES IN SPECIAL CASTING SHOPS

Об'єктом дослідження є плавильно-заливальна система цехів спеціальних видів лиття. Процес розглядався на основі імітаційного моделювання потреби кокільних машин або машин лиття під тиском в розплав і можливостей плавильних і роздавальних печей забезпечити цю потребу. Моделювання здійснювалося на основі типових рішень по застосовуваних марках печей для виготовлення алюмінієвих сплавів в кольороволіварних цехах машинобудівного підприємства, що спеціалізується на виготовленні лиття в металеві форми для виробів машинобудування.

В результаті імітаційного моделювання отримано опис впливу інтенсивності заявок на розплав з боку кокільних машин або машин лиття під тиском, і часу виконання цих заявок на сумарні витрати по реалізації технологічного процесу. Запропоновано сумарні витрати визначати як суму витрат, пов'язаних з витратою технологічної електроенергії, і витрат, пов'язаних з імовірним простоем машин через брак металу. Причому друга складова відображає вимоги до продуктивності машин в умовах реальної їх експлуатації. Тому сумарні витрати на реалізацію процесу кокільного лиття або лиття під тиском в частині, що стосується узгодженості роботи елементів плавильно-заливальної системи, обрані в якості критерію оптимізації її функціонування.

Запропоновано плавильно-заливальну систему розглядати як систему масового обслуговування (СМО) з відмовами. Таке уявлення є найбільш жорстким з точки зору вимог до забезпечення заданої продуктивності. За допомогою дослідження поверхні відгуку вирішена оптимізаційна задача по узгодженості інтенсивності заявок на розплав і часу їх виконання, що мінімізує сумарні витрати на реалізацію технологічного процесу. Отримано локально-оптимальні технологічні рішення, що дозволяють технологам обирати найбільш раціональні рішення по веденню кампанії плавки з використанням роздавальних печей ємністю 0,16–0,25 т. Такі рішення забезпечать можливість зниження витрат на виготовлення алюмінієвого лиття.

Ключові слова: спеціальні види лиття, лиття під тиском, роздаткові печі, плавильно-заливальна система, система масового обслуговування.

1. Introduction

In the conditions of mass production of special casting types in shops with chill machines or injection casting machines, it is necessary to ensure the specified performance. However, it is difficult to organize the process in

such a way as to harmonize the quality requirements of the resulting castings. If the decisions on the organization of the process are wrong, there may be additional costs for the process. For example, the overrun of energy carriers or material resources is possible. Therefore, it is important to develop solutions in the field of control of

melting and casting systems in such a way as to ensure consistency between different management quality criteria – performance and energy costs.

2. The object of research and its technological audit

The object of research is the melting and casting system of special casting shops. This system includes melting furnaces, holding furnaces, die-casting machines or die casting machines. Technological audit may consist in the timing of the technological process, which is needed to determine two main parameters – the intensity of applications for the melt (λ , t/h) and the average service time of the application ($\mu = T^{-1}$, h⁻¹). In the absence of real data, simulation modeling is possible, allowing for typical performance indicators of special casting shops to obtain estimated performance characteristics of the melting and casting systems. This approach is justified, since the technical characteristics of the furnaces used are as well known as the technological capabilities of the used typical equipment.

3. The aim and objectives of research

The aim of research is determination of the optimal functioning parameters of the melting and casting system for special casting shops equipped with chill machines or injection casting machines.

To achieve this aim it is necessary to solve the following objectives:

1. To determine the ranges of typical technical characteristics of the equipment for melting and casting systems.
2. To select optimization criteria.
3. To conduct simulation modeling of the functioning of melting and holding furnaces.

4. Research of existing solutions of the problem

Since the melting and casting systems must provide the machine with high-quality alloy, special attention is paid to the technological issues of alloy production. They, in turn, relate either to a targeted impact on the processes of structure formation [1, 2], or to a complex effect on the melt in the process of its solidification [3, 4]. However, issues related to the effect of the time of the proposed technological operations on the probability of equipment downtime are not considered. Obviously, this question is connected with the possibility of choosing a rational working space and capacity of the furnaces. In this part, it is necessary to talk about the possibility of creating new design solutions for furnaces, which are offered by the world's leading manufacturers. In particular, BottaEngineeringSrl (Italy) electric furnaces are proposed in [5], in which the melting chamber is a monolith of special refractory concrete resistant to aluminum. The issue of energy saving is solved by high-quality thermal insulation of the working space of the furnace. The furnace temperature is controlled automatically by two thermocouples, one of which is located in the pocket for metal sampling, and the other, which performs a safety function, in the furnace vault. In order to optimize the operating temperature, combustion control can be carried out using an on-off, minimum-maximum method or with modulation.

FometSrl (Italy) offers CR induction crucible furnaces operating at an industrial frequency for melting, holding and processing any non-ferrous metals [6]. High-performance melting furnaces for melting and storing molten aluminum, furnaces for injection molding machines, as well as large bath furnaces with electromagnetic or mechanical molten aluminum circulation pumps, are offered by NovacEngineeringSrl (Italy) [7]. Analysis of these proposed melting equipment solutions allows to see main trend: an attempt to automate and universal design and technological solutions. Such solutions are considered as an alternative to traditional approaches, which are characterized by a lack of a weak degree of automation and integration with other technological systems of the shop. The direction of development is seen in the combination of technological operations [8, 9]. For example, it should be noted the revolutionary model of the company CIME CrescenziInductionMeltingSrl (Italy). CAP (CorelessAuto-Pour) is a crucible furnace that can perform automatic casting under pressure in combination with any automatic molding line. In this furnace, an elliptical coil is used to improve the heating of the channels and increase the overall energy efficiency. As a result, in the SAR furnace channels are in the magnetic field of the induction coil and are heated constantly. Constant and uniform heating makes it possible to begin casting at any time, since metal hardening or slag sticking are excluded. Maintaining a constant temperature reduces overheating to a minimum and facilitates self-cleaning of the furnace. This helps to increase the time between the replacement of the lining. One of the features of the furnace is that in the absence of a metal ballast bath, the automatic melting furnace can be completely de-energized on weekends, after which work can be resumed with a semi-liquid or solid charge [8].

Optimal control of the metallurgical process is a feature of the solutions proposed in [9]. In particular, the DuoMelt system allows for a smooth distribution of the power of the frequency converter between two furnaces operating in series. This leads to the possibility of full utilization of 100% of the rated power constantly, to shorter downtimes, and therefore to an increase in melting performance. Among the advantages of such solutions should be noted the possibility of simultaneous melting, holding and casting, as well as maximum flexibility and elimination of pauses when switching modes. Control using the DuoControl system implies computer integration. This ensures shorter downtimes, which results in higher melting rates. This is made possible by simultaneous melting, holding and casting.

The continuous monitoring and automatic control for all required functions and technological operations of the furnace during the melting cycle is provided by the JOKS melting processor. This processor controls the exchange of data and information with higher-level control systems and provides logging and evaluation of operational data. Such solutions can be recognized as successful, however, the models and the IT solutions implemented on them in terms of automation and computer integration are not disclosed by manufacturers. Obviously, simulating the operation of the melting and casting system, it is necessary to take into account that the furnaces are energy-technology and heat engineering complexes, regardless of the method of energy supply [10, 11]. Their thermal performance and energy capabilities can have a decisive influence on the

melting quality and the ability to provide consumers with a given amount of melt with the required properties.

5. Methods of research

As a research method, a mathematical apparatus is chosen that describes the operation of queuing systems, adapted to simulate the operation of melting systems in casting shops [12]. In particular, the most unfavorable from the point of view of evaluating the capabilities of the description system is considered – its representation by a queuing system with failures (QS). In accordance with this, analytical and economic performance criteria are calculated [13].

To evaluate the analytical criteria, the following parameters are calculated:

- the initial probability of the state of the system, P_0 ;
- probability of failure in the service application, P_f ;
- intensity of the flow of lost applications, $Q_{l.a}$;
- probability that the application will be served, q ;
- intensity of the flow of served applications, $Q_{s.a}$;
- average number of busy channels, m_k ;
- system load factor, Ψ .

$$P_0 = \left(1 + \rho + \frac{\rho^2}{2!} + \frac{\rho^3}{3!} + \frac{\rho^4}{4!} + \dots + \frac{\rho^n}{n!} \right)^{-1}, \tag{1}$$

where n – the number of channels in the QS service node.

$$P_f = P_0 \frac{\rho^k}{k!}, \tag{2}$$

where k – the number of the channel that serves the request ($k=1, 2, 3, \dots, n$).

$$Q_{l.a} = \lambda P_f, \tag{3}$$

$$q = 1 - P_f, \tag{4}$$

$$Q_{s.a} = \lambda q, \tag{5}$$

$$m_k = \frac{\lambda q}{\mu} = \rho q, \tag{6}$$

$$\Psi = \frac{m_k}{n}, \tag{7}$$

where Ψ – the system load factor (analogue efficiency).

To assess the economic criterion, the total cost of operating the system is calculated:

$$W(n) = C_1 \lambda P_f(n) + C_2 [n - m_k(n)], \tag{8}$$

where C_1 – the value of costs associated with system downtime; C_2 – the amount of costs associated with operating the system.

Criterion (8) is minimized with respect to n , i. e., a value of n^* must be found which turns criterion (8) to a minimum. The values found in this way form a vector of output variables to obtain a regression equation of the form $n^* = f(\lambda, \mu)$. The choice of ranges of values of these variables is determined by the capa-

bilities of holding furnaces with a capacity of 0.16–0.25. Each such pair of input variables, selected in a special way, forms a point of the central orthogonal plan of the experiment. Consequently, an active experiment can be implemented to construct a regression equation. The ranges of input variables are chosen as follows: $x_1 = \lambda = [0.1; 0.5]$, $x_2 = \mu = [0.03; 0.07]$, the rationing is performed by a standard procedure that translates the specified ranges of natural values into $[-1; +1]$. Optimization is performed by a ridge analysis based on the parametric description of the species [14]:

$$\begin{cases} x^*(\lambda) = (\lambda I - A)^{-1} a, \\ r(\lambda) = \sqrt{x^{*'} x^*}, \\ y^*(\lambda) = a_0 + 2a' x^* + x^{*'} A x^*, \end{cases} \tag{9}$$

where a_0, a, A – coefficient estimates in the regression equation; $x_i^* = a_i (2\lambda)^{-1}$ – suboptimal values of input variables – λ, μ ;

$$r = \sqrt{r^2}, \quad r^2 = \sum_{i=1}^n [a_i (2\lambda)^{-1}]^2$$

– constraints in the factor space $\lambda-\mu$;

$$y^* = a_0 + \sum_{i=1}^n a_i^2 (2\lambda)^{-1}$$

– suboptimal values of output variables, $y^* = n^*$.

6. Research results

The results of the ridge analysis, which are final in solving the problem, are shown in Fig. 1, 2.

From Fig. 1, 2 it can be seen that in the area of restrictions imposed by the plan of the experiment, the optimal solutions are on the ridge lines I and IV. In this case, the first parametric equation of system (9) can be used to select pairs $(\lambda-\mu)$ that satisfy the optimal solutions $y^* = n^*$.

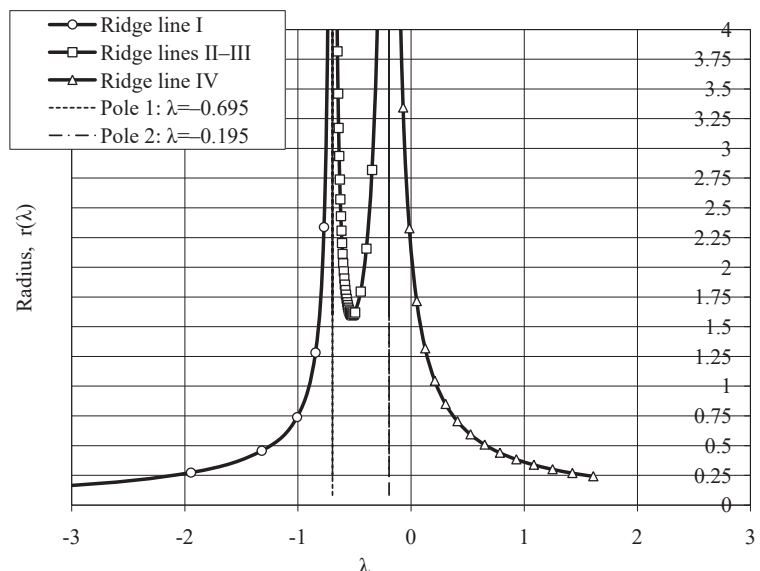


Fig. 1. Parameter description of restrictions on input variables

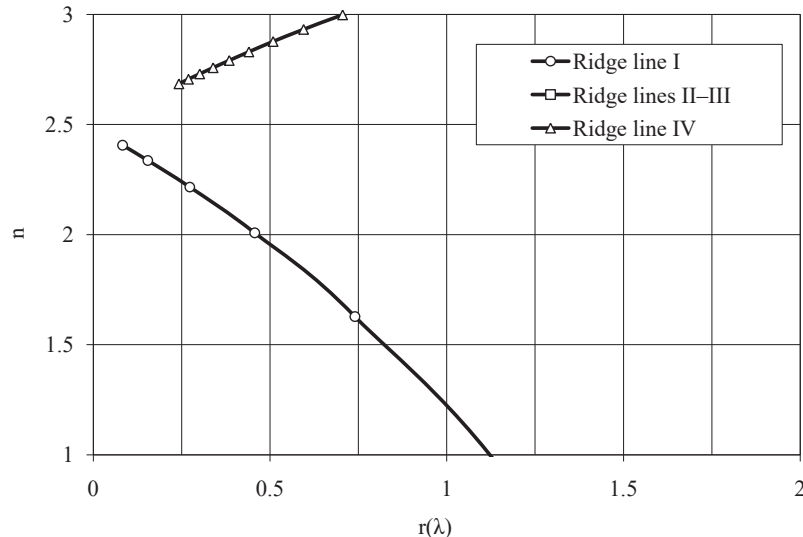


Fig. 2. Parametric description of optimal solutions

7. SWOT analysis of research results

Strengths. The strength of this research is the ability to determine the optimal load of furnaces by a compromise criterion of minimizing total costs for downtime and energy consumption. The resulting solutions are analytical and allow to perform calculations with the actual performance of the melting and casting systems in the casting shop. This opens up prospects for reducing the cost of production.

Weaknesses. Weaknesses of this research are related to the fact that the obtained solutions are acceptable only within the considered range of values of the input variables. If the intensity of applications for the melt and the average time of their service are outside the limits of this area, the results will differ from received. Using the obtained optimal solutions without taking this circumstance into account may lead to incorrect conclusions regarding the expedient loading of the furnaces.

Opportunities. Additional opportunities when using the above results in an industrial environment are associated with the rationalization of the organization of the melting campaign. The organizational and technical solutions adopted at the same time can contribute to the improvement of the performance of the melting and casting systems of the casting shop.

Threats. Obvious risks when using the obtained results are associated with the need to make changes to the management system of the casting shop. And it is mandatory to adapt theoretical solutions to the real performance of the melting and casting equipment and chill machines (injection molding machines). Any wrong decision in this case can lead to unnecessary costs.

8. Conclusions

1. It is established that typical solutions for melting equipment – melting and holding furnaces – in aluminum casting shops involve the use of furnaces for which the intensity of applications for the melt is (0.1–0.5) t/h, and the reciprocal of the average time service requests is in the range (0.03–0.07) min^{-1} .

2. As an optimization criterion, it is necessary to choose a compromise criterion that is formed from the costs of process electricity and costs due to equipment downtime due to the absence of a melt in a given amount. These two components of the criterion are competitive in relation to each other.

3. Imitating modeling establishes optimal solutions for loading furnaces. They are determined depending on the intensity of applications for the melt from the side of the chill machines or injection molding machines, and the average execution time of these applications. It is shown that such optimal solutions can be written in the parametric form $n^* = \varphi(r(\lambda))$. This representation allows to calculate the optimal furnace load depending on the restrictions imposed by the ranges of input variables. Such variables are the operating parameters of the melting and casting systems: the intensity of applications for the melt and the average time of their service, depending on the technical characteristics of the used furnaces.

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