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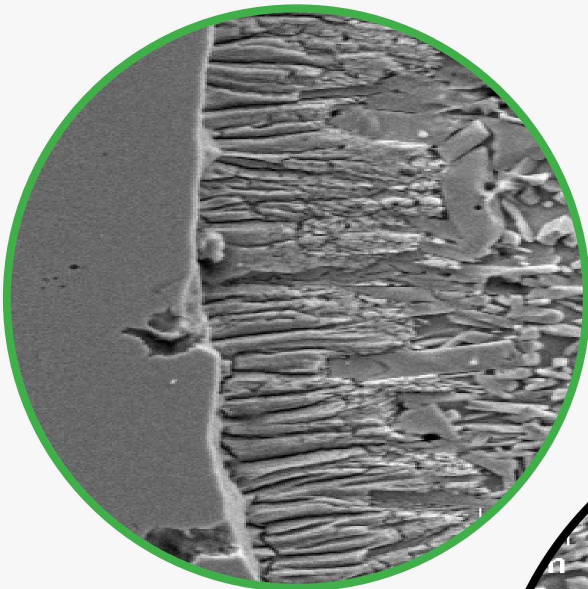

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An IT System for the Remote Burden Optimization of Foundry Furnaces

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Abstract

The burden calculations for foundry furnaces are one of the most important steps in preparing the production of liquid casting alloys. These calculations, due to the usually large number of input materials and chemical elements, are realized by numerical methods. These methods are implemented in some spreadsheets, universal mathematical programs or in specialized programs for foundry engineering. The paper describes a computerized system for remote calculations of optimal burden. The technological, economic, and organizational features of implementing IT system have been presented, also taking into account its safety of use.

Keywords:
IT system for remote optimization, burden optimization for foundry furnaces

1. INTRODUCTION

Determining the optimal burden of an assumed chemical composition requires the formulation of an optimization task by defining an objective function (usually minimum charge cost) and a constraints system. Various mathematical models of such an optimization task have been described in publications including [1–4]. To solve such tasks, the following can be used:

- optimization module available in some spreadsheets (e.g. Solver in Excel/MS Office [5] or Solver in Calc/Libre-Office [6]);
- mathematical package (e.g., Mathematica by Wolfram Research [7], MATLAB by MathWorks [8]);
- specialized program ordered by foundries.

Using the optimization module contained in a spreadsheet as well as the optimal value search function in a mathematical package requires the ability to define a mathematical model. With the high dynamics of input data changes (changing the number and parameters of input materials, changing the list of chemical elements used in calculations), the use of these IT tools is inefficient. The much more effective realization of calculations in the given foundry is possible when a specialized program for burden optimization is implemented. However, it involves the need to purchase such a system, its constant servicing, updates, etc. Programs classified in this category can be implemented as single-user or multi-user programs, with one or more levels of user privileges to particular functions. They can either be installed without any additional security or protected against unauthorized use and/or copying using, for example, dongles or network software licensing systems. The features of the above solutions have been the basis for the preparation of this paper presenting a universal computer system with remote burden optimization for foundry furnaces.

In the following part of the article the assumptions of this system and the way of its implementation will be described. The benefits of technologists using a remote calculation system in foundries will also be characterized.

2. FUNCTIONAL ASSUMPTIONS OF THE IT SYSTEM FOR REMOTE BURDEN OPTIMIZATION

The computation of the minimum cost batch bearing for the assumptions is to be performed by a server located at a selected computing center that authorized users can connect to via Internet connections. The developed system has the following features:

- preparation of input data for optimization calculations is performed by a program installed on a user's computer; this program is also used to obtain a connection to the calculation server, send the input data and receive the obtained calculation results from the server;
- the connection between a client and the server programs takes place over a computer network via the TCP/IP protocol on a specific port number;

- calculations are performed by a program installed on the server; this program listens for connection requests from each client program and, without human intervention, after authentication and input validation, performs the calculations and then generates a report as an electronic document (in PDF format) and sends it to a client program from which the job was run;
- the program located on the server works continuously (24 hours a day) and is protected against unauthorized access and copying by means of a dongle on the USB port;
- there is also a database (PostgreSQL) installed on the server, containing data on the authorized users of the system along with additional information such as: the range of allowed calculation functions, the allowed number of calculation runs (if applicable), a date range in which a user can use the system and other organizational and possibly billing data;
- the program on the server runs under the control of the 64-bit MS Windows operating system;
- the program performs automatic cyclic backups of the database and reports from optimization calculations.

3. MAIN PROGRAM INSTALLED ON THE SERVER

The program installed on the server performs the following tasks:

- receives TCP network computation requests on a port with a specified number along with an XLSX format file (MS Excel);
- authorizes, in cooperation with database, the rights of a specific user to run a computational procedure;
- verifies the correctness of the input data;
- performs calculations using the selected fuzzy optimization method [2–4];
- generates a report of the calculations performed and sends a PDF file containing the input data and results to the user's computer;
- saves information about the actions performed in the database.

Figure 1 shows a view of the program window, developed and executed by the author of this publication, installed on a server named *RBC Server*.

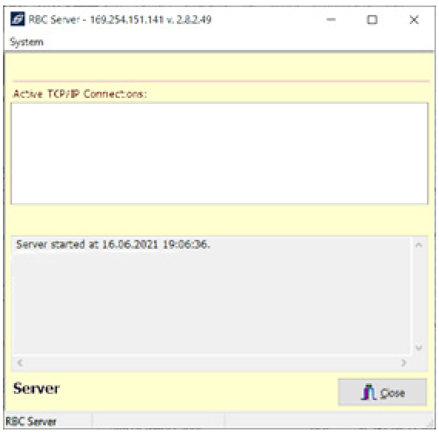


Fig. 1. View of RBC Server program window

This program was written in Embarcadero's *RAD Studio* 10.4.2 development environment [9]. *DataSnap* technology [10] is used to create networked multi-user applications that can listen for Internet requests from client programs and execute them. The program window displays only information about established connections and the status of successively performed actions. The *RBC Server* program is protected against unauthorized use and copying by a Sentinel HL NetTime dongle [11] connected to the server's USB port. A view of such a key and its basic performance parameters are shown in Figure 2.

RAM	4 KB
ROM	2 KB
Max. users	10, 50, 250+
Max. licenses	231
Real Time Clock	

Fig. 2. View and basic parameters of the Sentinel HL NetTime dongle [11]

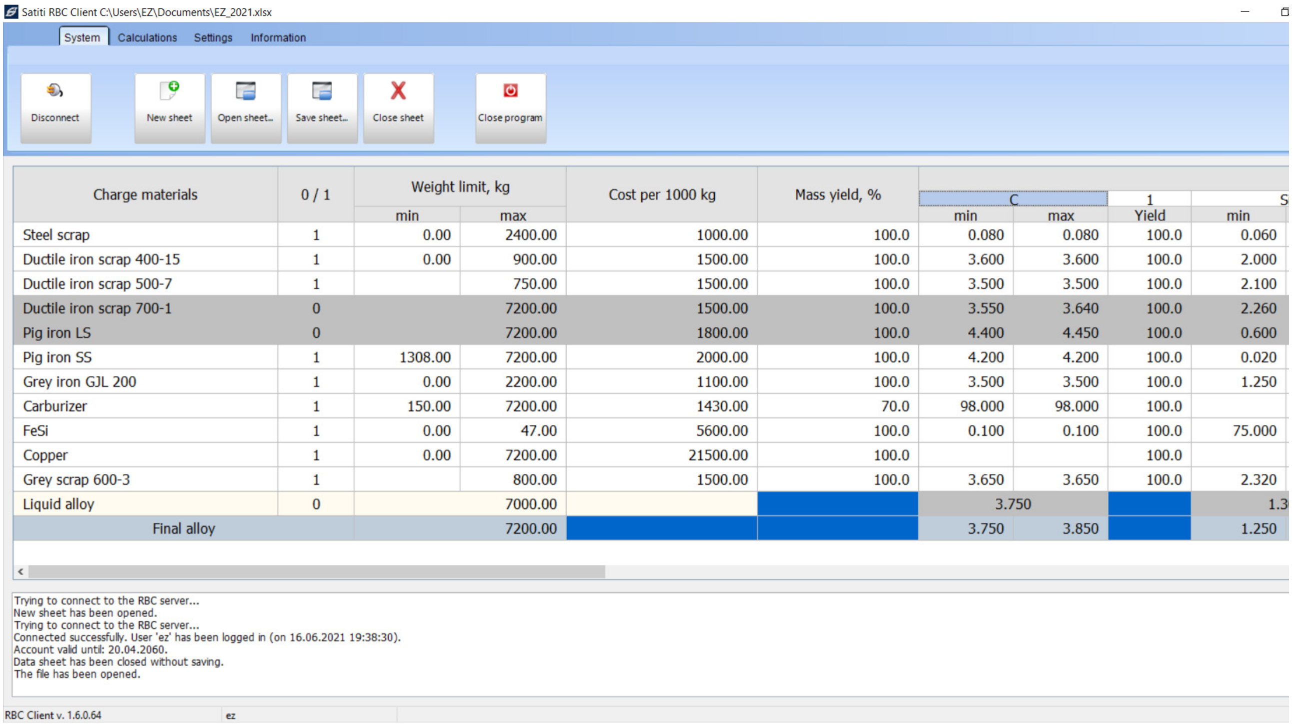
The *Sentinel HASP Vendor Suite* [12] is used to secure *RBC Server* with a Sentinel HL NetTime dongle and to set and subsequently update the key's important operating parameters. Special Master and Developer dongles are also required to program this key. The HL NetTime key not only allows the specification of a number of RBC Server users, but also a license validity period which can be extended accordingly. This is especially important when installing the program on a server hosted by a third party. When a license expires, the program and the dongle can no longer be used.

4. CUSTOMER PROGRAM

The main tasks performed by the client program include:

- establishing a remote connection to *RBC Server*;
- authentication and reading the functional privileges from the server;
- creating a new, reading or modifying a stored input data file (in XLSX format);
- selection of a variant of optimization calculations of the burden for foundry furnace;
- sending the XLSX file to *RBC Server*;
- receiving a PDF file with the calculation results and displaying it on a client's computer in the default PDF viewer;
- the possibility to calculate the chemical composition of a charge for individually specified limits of particular input materials.

All communications between *RBC Client* and *RBC Server* are performed using SSL encryption. The connection and data exchange between *RBC Server* and the *PostgreSQL* database located on the server is also encrypted.



Charge materials	0 / 1	Weight limit, kg min	Weight limit, kg max	Cost per 1000 kg	Mass yield, %	C min	C max	Yield	S min
Steel scrap	1	0.00	2400.00	1000.00	100.0	0.080	0.080	100.0	0.060
Ductile iron scrap 400-15	1	0.00	900.00	1500.00	100.0	3.600	3.600	100.0	2.000
Ductile iron scrap 500-7	1		750.00	1500.00	100.0	3.500	3.500	100.0	2.100
Ductile iron scrap 700-1	0		7200.00	1500.00	100.0	3.550	3.640	100.0	2.260
Pig iron LS	0		7200.00	1800.00	100.0	4.400	4.450	100.0	0.600
Pig iron SS	1	1308.00	7200.00	2000.00	100.0	4.200	4.200	100.0	0.020
Grey iron GJL 200	1	0.00	2200.00	1100.00	100.0	3.500	3.500	100.0	1.250
Carburizer	1	150.00	7200.00	1430.00	70.0	98.000	98.000	100.0	
FeSi	1	0.00	47.00	5600.00	100.0	0.100	0.100	100.0	75.000
Copper	1	0.00	7200.00	21500.00	100.0			100.0	
Grey scrap 600-3	1		800.00	1500.00	100.0	3.650	3.650	100.0	2.320
Liquid alloy	0		7000.00			3.750			1.3
Final alloy			7200.00			3.750	3.850		1.250

Fig. 3. View of RBC Client window with sample input data

Figure 3 shows a window view of the *RBC Client* with the sample input data, while a part of the PDF file with calculation results is shown in Figure 4.

Figure 5 shows a view of the main window of the client program (*RBC Client*) before establishing an authorized connection to *RBC Server*.

The input data for the optimal burden calculation includes the following information:

- names of change materials;
- in the '0/1' column whether the input material should be considered for the calculation or not;
- the limit on the mass contribution of a given component to the input [kg];
- unit cost of each charge material;
- the chemical composition of each material, i.e. the range of each chemical element content to be considered in the calculation [%];
- metallurgical yield value [%];
- yield values of individual chemical elements [%];
- the mass [kg] and chemical composition [%] of the liquid metal from the previous melt;
- the requested values of the mass [kg] and chemical composition [%] of the liquid melt after melting.

Once the connection to *RBC Server* has been established and the user has been properly authenticated, it is possible to select the optimization calculation mode in the *RBC Client*. It is now possible to determine the optimal burden (with minimum cost) and to calculate the minimum mass of charge to correct the incorrect chemical composition of the liquid melt in the foundry furnace (Fig. 4).

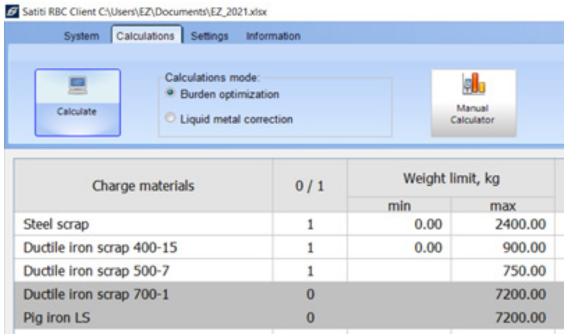


Fig. 4. Fragment of a window with selection of optimization calculation mode

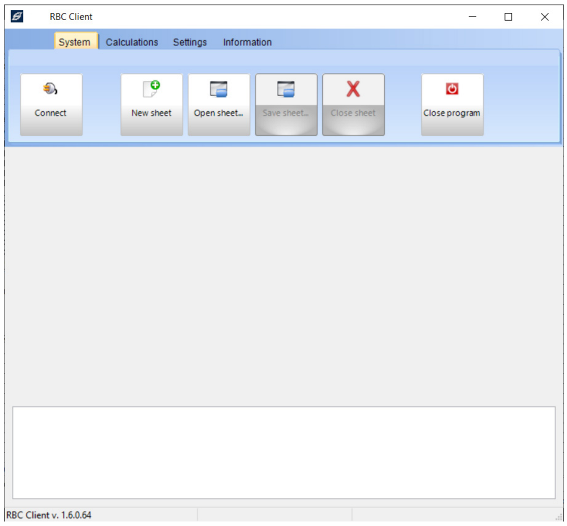


Fig. 5. View of RBC Client main window before logging on to RBC Server

After the *RBC Server* program performs the calculations, a PDF file is automatically sent to a client computer, a part of which is shown in Figure 6. This file can be opened by the default PDF viewer and can be saved or printed by a customer.

User:	ez
Input file name:	C:\Users\EZ\Documents\EZ_2021.xlsx
Date of calculations:	16.06.2021 22:47:47
Report file name:	2021-06-16 22_47_47.ez.EZ_2021.xlsx.pdf

Burden optimization results

Optimal burden exists ✔

Target alloy: Final alloy

Charge material	Weight, kg	%
Steel scrap	2400.00	33.13
Ductile iron scrap 400-15	0.00	0.00
Ductile iron scrap 500-7	571.95	7.89
Pig iron SS	1308.00	18.05
Grey iron GJL 200	2140.04	29.54
Carburizer	150.00	2.07
FeSi	47.00	0.65
Copper	12.19	0.17
Grey scrap 600-3	615.82	8.50
	7245.00	100.00

Weight of liquid metal after melting, kg: 7200.00

Cost of materials to melt (per 1 t): 1373.82

	Chemical composition, %	
Element	Assumed	Calculated
C	3.750 ÷ 3.850	3.850 ÷ 3.850
Si	1.250 ÷ 1.350	1.250 ÷ 1.250
Mn	0.000 ÷ 0.140	0.087 ÷ 0.087
P	0.000 ÷ 0.030	0.019 ÷ 0.019
S	0.000 ÷ 0.020	0.011 ÷ 0.011
Cu	0.300 ÷ 0.370	0.300 ÷ 0.300

Fig. 6. Excerpt from the report (PDF file) with calculation results

5. SUMMARY

The application of tools for creating client-server applications (*DataSnap* technology in *RAD Studio* environment) with *PostgreSQL* database and implemented methods of burden optimization made it possible to create an effective remote IT system for determining charges for foundry furnaces. The application security used (SSL protocol, network and time hardware key protection) also allows the system to be used for commercial purposes. The created and practically tested IT system confirmed the easy management of users' authorizations, high efficiency of calculations' realization and advantages resulting from the possibility of automatic calculations' realization in any time. This allows it to be used regardless of where users' computers are located in the global computer network.

The developed system can also be used for other computational tasks.

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Directions of the Development of the Metallization of Iron Alloy Products

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Abstract

The article discusses the future of the production of protective coatings based on the hot-dip galvanizing of iron-carbon alloys, such as steel or cast iron. Currently exploited zinc deposits will be exhausted in the next two decades and it will be necessary to start the exploitation of new deposits in order to maintain the supply or quantity of Zn on the global market. In both cases, it will be related to the increasing cost of zinc on world markets. Zinc-based protective coatings (one of the best corrosion protection methods) constitute almost 50% of the world's zinc consumption. Economic issues with the constant increase in the price of Zn will force the change or modification of hot-dip galvanizing technology. The article presents data on the production, consumption and development of zinc prices on the global market. Possible directions are presented which producers of zinc coatings will have to follow in order to maintain sales markets, such as the modification of chemical compositions of protective alloys which could be an alternative to pure zinc coatings and the possibility of limiting zinc consumption based on the influence of the surface of galvanized elements, i.e. its metal matrix, and surface roughness.

Keywords
hot-dip galvanizing, aluminizing, protective coatings, zinc

1. INTRODUCTION

Galvanizing is the most popular method to provide protection for Fe-C alloys against corrosion, especially of steel, but also cast iron or cast steel. Protective coatings consume 50% of global zinc production (Fig. 1).

Due to the very important role of zinc in the global corrosion protection industry, an analysis of the quantity, availability and price of this element was carried out, as well as the direction of potential development of the hot-dip galvanizing industry.

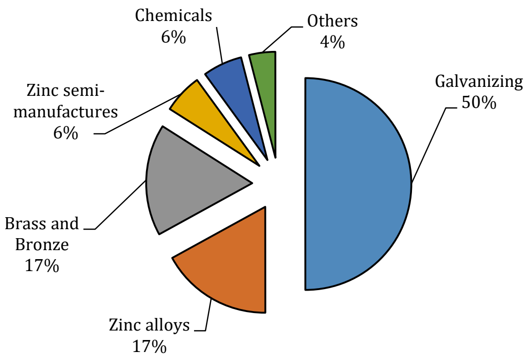

Fig. 1. End uses of zinc [1]

2. CASE STUDY

Zinc production shows an upward trend. In 1990 7.15 mln ton mine and 7.18 mln smelter production. In 2000 8.77 mln ton mine and 9.03 mln ton smelter production. In 2010 12.3 mln ton mine and 12.9 mln ton smelter production (Fig. 2).

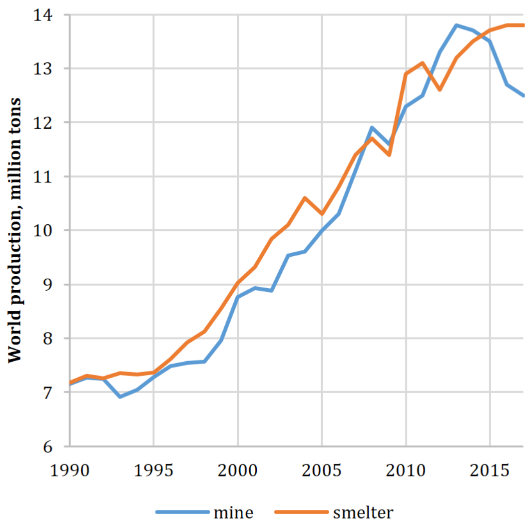

Fig. 2. Production of zinc (mine and smelter) since 1990 to 2017 [2]

The growing production of zinc is a symptom of the increasing demand for this element. Figure 3 shows the global consumption of zinc in the years 2004–2018.

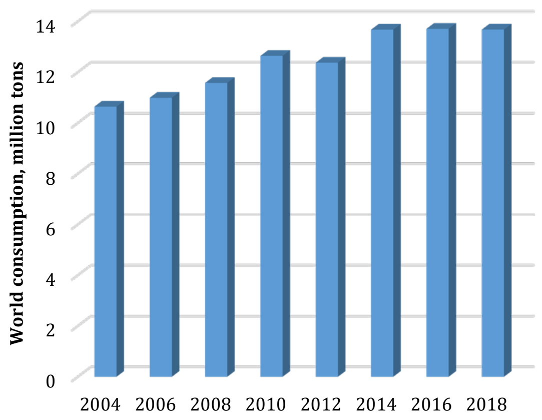

Fig. 3. Global consumption of zinc since 2004 to 2018 [3]

The constantly growing consumption of zinc also affects the price of this element. Figure 4 presents zinc prices from the last 14 years. The highest price was November 24, 2006 4,619 USD, the lowest in December 12, 2008 1,072.25 USD per ton.

In Table 1, production and reserves of zinc from 2004 to 2018 are compared for the seven world largest producers among the ten largest world zinc producers. Values of the reserves in this table means that these deposits are ready for mining at any time.

In order to understand the problem, it is necessary to present the unique nature of corrosion protection afforded by zinc coatings in relation to other protection methods. Zinc coatings provide active (cathodic) protection [4–6]. Over time, the zinc layer is lost and the protected surface does not corrode. This is a considerable advantage in relation to, for example, paint coatings that provide only passive (anodic) protection. The key to a flawless coating is to carry out proper chemical surface preparation.

Fig. 4. Zinc prices since December 1, 2005 to February 12, 2021 [7]

Table 1
Global production and reserves of zinc from 2004 to 2018 [3]

Country	Mine (ton/year)					
	2004		2011		2018	
	Production	Reserves	Production	Reserves	Production	Reserves
United States	739,000	30,000,000	769,000	11,000,000	790,000	11,000,000
Australia	1,300,000	33,000,000	1,520,000	70,000,000	940,000	64,000,000
Canada	790,000	11,000,000	612,000	7,800,000	340,000	3,000,000
China	2,300,000	33,000,000	4,310,000	43,000,000	4,300,000	44,000,000
Kazakhstan	360,000	30,000,000	495,000	10,000,000	390,000	13,000,000
Peru	1,200,000	16,000,000	1,260,000	18,000,000	1,600,000	21,000,000
Mexico	460,000	8,000,000	632,000	16,000,000	650,000	20,000,000
Other countries	2,400,000	59,000,000	3,207,000	74,300,000	3,840,000	49,200,000
World total	9,600,000	220,000,000	12,800,000	250,000,000	13,000,000	230,000,000

There are many ways to apply a zinc coating, such as hot zinc spray, electrogalvanizing or sherardizing. However, the immersion method (hot-dip) allows the most durable, resistant protective coating with the longest operating time to be obtained. Analyzing the data contained in the previous chapter, it can be concluded that global zinc consumption will stabilize at the level of 13.5-14 million tons (Fig. 3), although an upward trend and exceeding 14 million tons is more likely. World reserves of zinc from 2011 to 2018 decreased by 20,000,000 tons which means it still relies on existing mining areas. Assuming a continuous extraction of 13,000,000 tons per year, it can be concluded that the present world reserves of zinc in the form of fossil deposits will be exhausted within 18 years. The decrease in the amount of zinc on the global market and increased world consumption will cause an increase in zinc prices on the global market, which will lead to an increase in the production cost of zinc coatings. For this reason, opportunities should be sought to introduce savings in the production of dip coatings to compensate for the increase in the price of zinc.

One possibility is to introduce elements other than zinc into the immersion bath. Such an element might be aluminum (Al). The following protective baths alloy containing this element are known as:

- Galfan alloy containing the addition of 5% Al and 0.05% mischmetal [8–10];
- Galvalume alloy containing the addition of 55% Al and 1.6% Si [11, 12];
- pure aluminum.

The addition of Al increases corrosion resistance in marine and industrial environments, and at the same time has a lower cathodic protection in relation to pure zinc coatings. An additional problem is the higher temperature of the treatment than in the case of zinc alloy due to the melting point of Al and the increased viscosity of the metallizing alloy. At present, using an Al addition to zinc or a pure Al alloy is unpopular due to the technologically difficult process of obtaining a protective coating comparable with the standard hot-dip galvanizing process. However, with the increase the price of zinc, aluminum alloys (Galfan, Galvalume etc.) may find greater use and the development of new techniques for applying a dip coating containing a greater amount of Al. may prove to be more economically advantageous.

Another option is to obtain more knowledge and control over the process of the protective coating growth in the hot-dip galvanizing treatment. This would allow for the adjustment of the treatment technology – the preparation of the surface before galvanizing (etching and fluxing), as well as the time of the immersion of the iron component in molten zinc to obtain the appropriate level thickness of the zinc coating. This is meant to meet the requirements of the purchaser and applicable standards, and to ensure that the losses of zinc during production in the form of hard zinc and zinc dust were as low as possible. For this purpose, it is worth focusing on the often overlooked aspect, i.e. the roughness and metal matrix of Fe-C alloy.

3. OWN RESEARCH

The hot-dip galvanization of GJS-500-7 cast iron with ferritic and pearlitic matrix and roughness of 16.7 and 43 mm was conducted according to the scheme shown in Figure 5 [4]. The test results are presented in Figures 6 and 7.

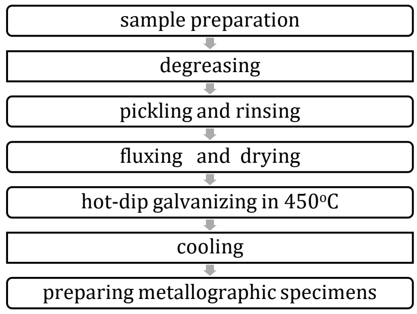

Fig. 5. Preparation of research samples

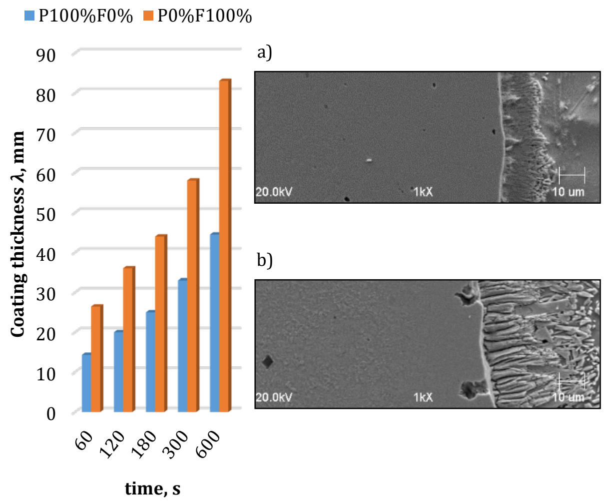

Fig. 6. Coating thickness of zinc phase alloy shaped on a ferritic and pearlitic metal matrix: a) matrix composition: P100%F0%; b) matrix composition: P0%F100% after 60-s hot-dip galvanizing

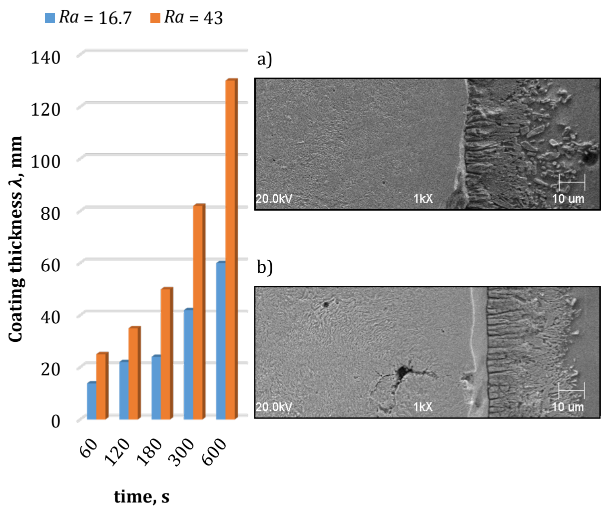

Fig. 7. Coating thickness of zinc phase alloy shaped on a surface roughness of 16.7 and 43 μm: a) 16.7 μm; b) 43 μm after 60-s hot-dip galvanizing

It can be observed (after 60-s of hot-dip galvanizing) that the differences in the obtained thickness of the alloy layer on the ferritic matrix in relation to the pearlitic matrix was 1.84:1. In the case of the influence of different roughness (with the same metal matrix) it was 1.79:1.

The knowledge of the structure of the Fe-C alloy would allow the shortening or extension of the immersion time in molten zinc in order to obtain the appropriate thickness of the protective layer. At the same time, the simultaneous galvanization of similar elements but with a different metal matrix or roughness could be avoided.

Calculations of the diffusion coefficient

Another important aspect is the assessment of the diffusion coefficient *D*. It is certain that the zinc consumption in the hot-dip galvanizing process depends on the diffusion coefficient. If we learn to calculate in a simple way (measure this parameter), we can start looking for a new zinc-saving technology of hot dip metallization. Calculation of this coefficient, which combines the surface quality of the galvanized element (surface roughness and the type of metal matrix) as well as the influence of the fluxing treatment, allows for the most comprehensive designation of the thickness of the protective layer that can be obtained in a given time. To determine the diffusion coefficient, the microsegregation aspect can be considered. Microsegregation is an uneven distribution of elements in crystallizing grains (crystals). Its cause is the difference in the solubility of the elements in the solid and liquid phases. The greater the distance between the liquidus and solidus lines in the equilibrium system, the greater the chemical heterogeneity of the crystallizing phase is to be expected. The influencing microsegregation factor is mass transport (diffusion) at the crystallization front (component separation). The analysis of the works [13, 14] shows that the description of segregation allows for theoretical consideration of the crystallization process for various conditions of the solid phase formation, using the Equation (1) describing the back diffusion parameter α.

$$\alpha = \frac{D \cdot t_L}{\lambda^2} \tag{1}$$

where:

- D – diffusion coefficient of the component in the solid phase;
- t_L – local crystallization time;
- λ – coating thickness.

Based on the assumed coefficient $\alpha = 0.87$ the solid-phase diffusion coefficient *D* was determined during galvanizing of cast iron with different (16.7 and 43 μm) roughness (Figs. 8, 9).

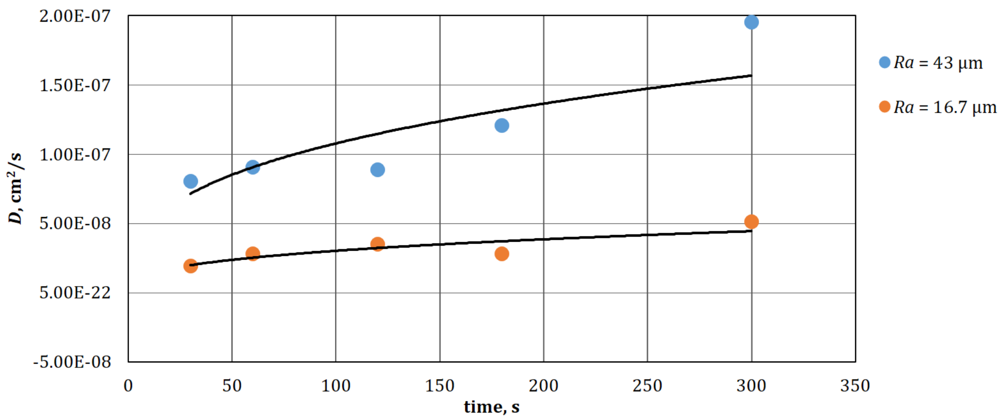

Fig. 8. Calculated diffusion during galvanizing from 30 to 300 s

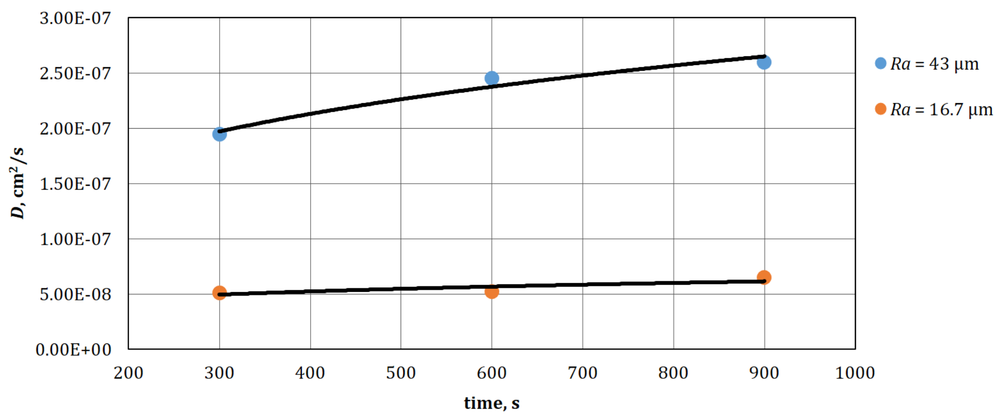

Fig. 9. Calculated diffusion during galvanizing μm from 300 to 900 s

4. SUMMARY

According to the above analysis, it can be concluded that:

- Zinc consumption and its price will increase.
- Without new zinc deposits, present reserves will be exhausted in less than 20 years with the current demand for zinc.
- Using a multi-component bath (addition of Al and other elements) will be more profitable with a rising price of zinc.
- The consumption of zinc during hot-dip galvanizing depends on the microstructure and surface roughness of the galvanized component.
- In the process of planning the galvanizing treatment, it is important to determine the rate of diffusion D, which allows us to know the rate of the growth of the zinc alloy layer.

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A New Flexible and Economic Technology for the Low Pressure Sand Casting of Steel Alloys

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Abstract

Low pressure casting is a very well established process for the casting of aluminium alloys. In the field of ferrous materials, however, the process has so far only found a few applications. The crucial reasons for this are the low flexibility and poor economic efficiency of the existing technologies. Since 2016, a new technology has been developed at the Foundry Institute of the TU Bergakademie Freiberg, in which an induction crucible furnace can be used as a melting unit and, in combination with a cover including a casting pipe, as a casting unit. The new technology stands out from existing low-pressure casting technologies for ferrous materials, particularly in terms of its flexibility and cost-effectiveness. The main focus of the activities was the development of a casting pipe as well as the verification of its lifetime, the elaboration and verification of process parameters and sequences as well as the upscaling of the technology for an industrial application. In all considerations, the focus was on both the technical feasibility and the economic efficiency of the process. The result is extensive expertise that can be used in the future to offer a finished product for industrial applications as a plug-and-play solution together with an induction furnace construction company.

Keywords:

Low pressure counter gravity casting, steel, thin wall casting, casting pipe

1. INTRODUCTION

Low pressure casting is a process that is widely used in industry. To date, however, it has been used primarily with the material aluminium. There are many reasons for this fact. One of them is the fact that the flow velocities of the melt can be influenced and the turbulence of the flow can be kept low by a controlled and rising mould filling. This is of extraordinary importance for the casting of high-quality and safety-relevant components, which have to meet high standards with regard to the absence of defects. Low turbulence during mould filling prevents oxide skin entrapments and additional hydrogen absorption in aluminium alloys. For alloys with a high tendency to oxidation and gas absorption, these aspects are the main reasons for the use of the low pressure casting process [1–6].

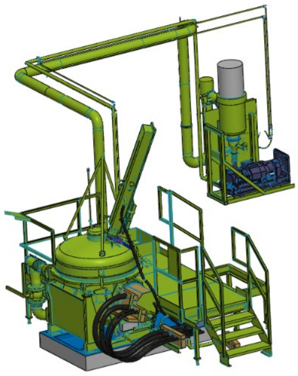
However, for most steel alloys, these two points of argument do not apply to the same extent, and it is also possible to meet the quality requirements for the components with the gravity casting process. The advantages of the low pressure casting process, apart from the controlled and lower-turbulent mould filling, which apply in their entirety to both aluminium and steel materials, are counterbalanced by higher plant and operating costs for technologies currently available on the market. Additional advantages of the low pressure casting technology compared to gravity casting of steel alloys are often regarded as so called soft facts because their monetary effect cannot be obviously quantified. One example is the significantly higher process stability. This leads to tighter tolerance limits, lower casting temperatures, the potential to cast smaller wall thicknesses and to significantly reduce the reject rate while at the same time significantly increasing output [6].

Consequently, the higher plant and operating costs of a process that is not absolutely necessary are put against a process that has been established for many years in countless foundries. The question arises: why should a steel foundry invest in the technology of low pressure casting? The aim of a variety of investigations in recent years was to better quantify some of the soft facts in monetary terms. Next to that the focus was in particular on the development of a new technology for the low pressure casting of steel alloys with significantly lower plant and operating costs than the technologies available on the market so far. This article presents the developed technology in comparison to already existing systems and evaluates the economic aspects of some of the relevant soft facts.

2. THE PILOT PLANT AT THE FOUNDRY INSTITUTE FREIBERG

At the end of 2017, a new vacuum induction furnace from the company Otto Junker was put into operation at the Foundry Institute of the TU Bergakademie Freiberg (TUBAF). The pilot plant can be used as a simple tiltable melting unit, whereby a special feature is that the melt can also be vacuum treated before tapping in order to remove dissolved gases. Figure 1 shows the furnace with the technical equipment for vacuum treatment.

a)



b)

Fig. 1. Furnace with the technical equipment for vacuum treatment: a) 3D-CAD drawing of pilot plant induction furnace with vacuum process lid [7]; b) photo pilot plant induction furnace with vacuum process lid in foundry shop of TUBAF

The entire furnace can also be over pressurised by up to 1.5 bar when ready for casting. For this purpose, an additional pressure control system and a suitable furnace lid were developed. It only has a central opening at the top. Various preliminary tests in the technical centre of the Foundry Institute in Freiberg made it possible to design this opening as an enclosure including suitable sealing surfaces for a ceramic casting pipe suitable for the low pressure casting of steel. The complete structural design of a corresponding casting pipe geometry was already realised in advance at the Foundry Institute. In parallel, extensive tests were carried out with a wide variety of refractory materials, particularly with regard to their erosion and thermal shock resistance behaviour, in order to determine a suitable casting pipe material.

Since commissioning, the induction crucible furnace has been used, among other things, to develop the low pressure casting of steel in combination with a casting pipe. The pilot plant has a power output of 150 kW and can melt 300 kg of steel at a time. Figure 2 shows the furnace including the platform in the configuration with the low pressure casting lid on top and the casting pipe installed. On the lid there is a casting bed on which the sand mould is positioned and thus placed on the casting pipe. With this construction, it is possible to cast moulds with a diameter of 950 mm. With 280 kg, the majority of the melt volume can be used for the low pressure casting itself.

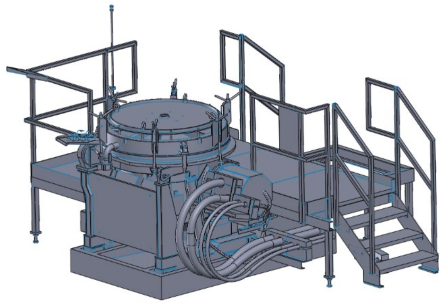


Fig. 2. Pilot plant induction furnace with low pressure casting lid [7]

Extensive test series were used to develop and optimise the technology of low pressure casting of steel with a crucible induction furnace in combination with a casting pipe for industrial use. The aim was to scale up the technology to enable series production on an industrial scale. The entire process of melting and casting was optimised in terms of procedures and adapted to the requirements of the foundry industry. Various parameters, which were determined through extensive series of tests, were incorporated into this development. These include, for example, the geometry and lifetime of the casting pipe and process sequences with regard to cycle time, which in turn fundamentally influences the design of a furnace system for industrial applications. Furthermore, all necessary parameters should be determined that allow a fundamental technological and monetary quantification of the advantage in comparison to counter gravity casting technologies already available on the market. Figure 3 shows the furnace system at the end of a casting batch. The low pressure casting lid is removed from the furnace with the built-in casting pipe to allow the charging of new material.

Fig. 3. Pilot plant induction furnace with lifted low pressure casting lid and casting pipe

3. COUNTER GRAVITY CASTING TECHNOLOGIES FOR STEEL ALLOYS

The following Table 1 is intended to provide an overview of the essential features of two counter gravity casting processes established on the market as well as the newly developed one, and to enable a comparison of the technologies with classical gravity casting. Each feature in gravity casting is assumed to be neutral (0) and a relative evaluation is made for each of the mentioned processes. The three processes listed are all classified as counter gravity casting. Processes that operate in the pressure range above atmospheric pressure are more accurately referred to as low pressure counter gravity casting (LPCGC) processes, while systems that operate below atmospheric pressure are referred to vacuum counter gravity casting (VCGC) processes.

3.1. Process control

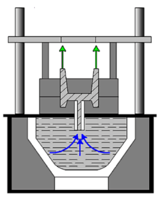
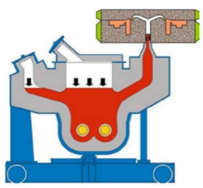
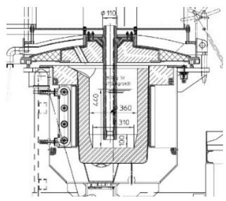
As shown in Table 1, all of the technologies listed offer equally clear advantages in terms of process control and mould filling characteristics compared to the gravity casting process. The positive evaluation of the process control results, for example, from the possibility of setting the pouring temperature and time very reproducibly for each pouring cycle. In the gravity casting process, the respective temperature changes constantly over a ladle journey. Moreover, in the case of stopper casting ladles, the existing pouring pressure and thus the volume flow and the flow velocity at the nozzle continue to decrease as the bath level falls.

3.2. Mould filling characteristics and non-gas-porous

The mould filling characteristics are very positive due to the upward movement and the fact that they can be controlled and monitored via a pressure curve.

The two systems working with overpressure are also characterised by a significantly reduced gas inclusion risk. This is mainly due to the mould filling characteristic, which is rising and very low in turbulence. The vacuum counter gravity casting process offers the same advantage with regard to gas inclusions, but also adds further risk for the same in the casted parts. Steel foundries in particular have naturally high scrap rates and low output due to the poor casting properties of the alloys. Both facts lead to a high recycling rate of the charged material. One consequence is a relatively high gas content in the melt. If the melt is filling the mould with the help of vacuum, it resembles a vacuum treatment of the melt in the mould. Especially if the melt is held in the mould until solidification with the help of the reduced atmospheric pressure, there is a greater risk of gas inclusions in the components. This effect can only be prevented by prior vacuum treatment or the use of decreased amounts of recycled material.

Table 1
Comparison of state of the art counter gravity casting technologies to gravity casting

Technology	Vacuum counter gravity casting	Existing low pressure counter gravity casting	NEW low pressure counter gravity casting by TUBAF
Illustration	 [8]	 [9]	 [7]
Process control	+++	+++	+++
Mould filling characteristics	+++	+++	+++
Non-gas-porous	0	+++	+++
Flexibility	0	---	0
Useable melt volume	---	---	-
Charge changing	-	---	0
Availability	---	--	+
Energy efficiency	+	--	+++
Casting pressure	+	+++	+++
Feeding effect	0	+	+
Casting yield	++	+++	+++
Cycle time	0	0	0
Asset cost	---	---	-
Cost of operation	---	--	+
Cost per part	---	--	++

Evaluation compared to gravity casting:
+++ much better; ++ better; + a little better
0 – comparable
--- much worse; -- worse; - a little worse

3.3. Flexibility, useable melt volume and charge change

In terms of flexibility, counter gravity casting technologies do not differ significantly from gravity casting. With regard to this aspect, only the low pressure casting process available on the market so far stands out negatively. The lack of flexibility is directly related to the useable melt volume. This is only approximately 50% of the capacity of the casting device, whereas it is above 90% in the process developed at the TUBAF. Consequently, it is much easier to change the alloy. The low pressure counter gravity casting device according to the state of the art usually has to be emptied at great expense for an alloy change. This process is very time consuming and thus reduces the availability of the system. In addition, a high proportion of recycled material is produced. With the newly developed low pressure casting process, a new batch can be directly assembled in the induction furnace in most cases. Only if the chemical analyses of the previous and next planned melt differ significantly does the small, non-pourable sump have to be removed.

3.4. Availability

The availability of the technologies differs significantly from each other. This is where the recently developed low pressure casting process stands out from the already established technologies. While casting often has to be interrupted in both vacuum counter gravity casting and existing low pressure casting systems, the new development enables almost uninterrupted casting. The reasons for the casting pauses in the established systems are, depending on the exact specific process design, an insufficiently long lifetime of the casting pipe or the necessity of recharging new material because the castable volume is exhausted. With the vacuum counter gravity casting process, it is possible to use single-use casting pipes that are automatically exchanged with each mould. The casting cycle itself can be designed quickly, but the resource efficiency is poor. In order to keep the operating costs moderate, especially due to the high consumption of casting pipes, these are very limited in their dimensions and only allow a low useable melt volume. This results in the need to frequently charge new melt into the casting device, which is associated with downtimes. This reduces availability. Alternatively, it is possible to use multiple use casting pipes. Current experience from the industry shows that only 4–5 castings are possible before the casting pipe fails. This fact leads to additional downtimes for changing the casting pipe. In principle this could be avoided, because casting pipes with larger dimensions and a longer lifetime could be applied and still be cost-efficient. Similar long interruptions of the casting phases have to be planned for the low pressure casting technology currently available on the market. With an exemplary casting weight of 50 kg per mould and a cycle time of the entire casting cycle of 60 s, a refilling process must take place approx. every 45 min for a useable melt volume of 2.25 to. This leads to a casting pause of approx. 15 min in each case. This process design already reduces the planned availability considerably. In this case, it reaches only 75%.

The newly developed low pressure casting technology takes up the widely used layout of induction melting plants, which are particularly cost-efficient in a so-called tandem mode of operation. Two induction furnaces with the same capacity, positioned directly next to each other, work together as an operational unit. While one induction furnace keeps the melt at pouring temperature, pours and has above 90% of its capacity available as castable melt volume, in the second induction furnace the next batch is charged, melted and adjusted to the correct chemical composition. The specific power of the furnaces is selected in such a way that, depending on the maximum casting weight and the associated cycle time of the individual casting process, the second furnace has melted the batch ready for casting with buffer time before the first furnace has used up its castable melt volume. As soon as this is the case, the furnace lid with mounted casting pipe is lifted from the first furnace, which has been poured empty, onto the second furnace, which is ready to pour. The second induction furnace can now proceed directly with casting while the first induction furnace takes over the function of the melting unit. The process described starts all over again. The furnaces have merely changed their function. In this way, it is possible to increase the planned availability tremendously. With reference to the previously selected example of a casting weight of 50 kg and a cycle time of the casting cycle of 60 s, only an interruption of the casting phase of approx. 3 min is necessary for the lid change every approx. 120 min. This results in a planned availability of 97.5%. Industrial processes are often evaluated on the basis of their OEE (overall equipment effectiveness). In the following, the influence of the different availabilities of the two low pressure casting technologies on this characteristic value will be clarified. Equation (1) [10] shows that the OEE results from the multiplication of availability, efficiency and quality.

$$OEE = Availability \times Efficiency \times Quality \tag{1}$$

With regard to the parameters of efficiency and quality, the two low pressure casting technologies do not differ fundamentally. Factors such as the general process structure, process control, the qualification of the employees and sometimes also maintenance management influence efficiency and quality far more than the difference in technology between the two processes themselves. For this reason, the same values are assumed for both processes. Half an hour of delay due to idling, short downtimes and reduced production speed per 8-hour shift as well as a reject rate of 10% are assumed as realistic values. This results in Equations (2) and (3):

$$Efficiency = 1 - \frac{0.5}{8} = 0.9375 \triangleq 93.75\% \tag{2}$$

and

$$Quality = 1 - 0.1 = 0.9 \triangleq 90\% \tag{3}$$

The OEE for the existing low pressure casting technology thus results as follows:

$$OEE = 0.75 \times 0.9375 \times 0.9 = 0.6328 \triangleq 63.3\% \tag{4}$$

The OEE for the new low pressure casting technology by TUBAF results equivalent:

$$OEE = 0.975 \times 0.9375 \times 0.9 = 0.8226 \triangleq 82.3\% \tag{5}$$

According to a generally accepted scale, an OEE below 65% means that the process is in need of major improvement. In this case, the top priority should be to analyse downtimes and stoppages. The range 65% to 85% represents the average of manufacturing operations, while an OEE above 85% is only achieved in processes that occupy a benchmark position. The OEE values calculated with certain assumptions for the two low pressure casting technologies thus illustrate on the one hand how unsuitable the low pressure casting system currently available on the market is from a production planning point of view and on the other hand that the newly developed technology has the potential to represent a benchmark process.

3.5. Energy efficiency

In terms of energy efficiency, all 3 counter gravity casting processes can stand out from conventional gravity casting processes. The reason for this is that the casting temperature can be set more precisely or within a narrower process window. In conventional gravity casting, 10 to 20 castings are usually made with one ladle, depending on the ladle size and casting weight. During this time, the melt cools down in the ladle. To prevent the last mould of a ladle to be cast from suffering cold runs, the first casting mould has to be casted much too hot. Depending on the process, in industrial practice this leads to an additional superheating of 40 K to 60 K. This overheating is not necessary in the counter gravity casting process because each casting can be carried out with the minimum possible casting temperature. The melt can be kept constant within a very narrow tolerance window with the help of the furnace control. Numerous casting tests with the newly developed low pressure casting technology on a pilot plant scale at the Foundry Institute in Freiberg confirm that a temperature window of ±8 K can be maintained in low pressure casting operation over a furnace journey. It can be assumed that this value can be reduced even further to ±5 K in an industrial-scale plant. Besides the effect of energy efficiency, a precisely adjustable temperature also contributes to quality improvement. Higher casting temperatures at the beginning of a ladle cycle statistically lead to more shrinkage-related porosity, poorer surface finishes and gas porosity. The newly developed low pressure casting process is also characterised by the fact that the same unit is used for melting and casting. This eliminates the need for any transfer and transport processes. This leads to a significantly leaner internal logistical structure and also to savings in electrical energy. When tapping a furnace into a ladle, a temperature loss of 50 K to 70 K occurs on an industrial scale. In addition, a disproportionately large temperature loss of the melt in the furnace and a higher burn-off of volatile alloy elements occur simultaneously due to larger active surfaces during the tilting and pouring process. This again leads to higher energy and alloying agent costs. Figure 4 illustrates the required superheat of different casting technologies.

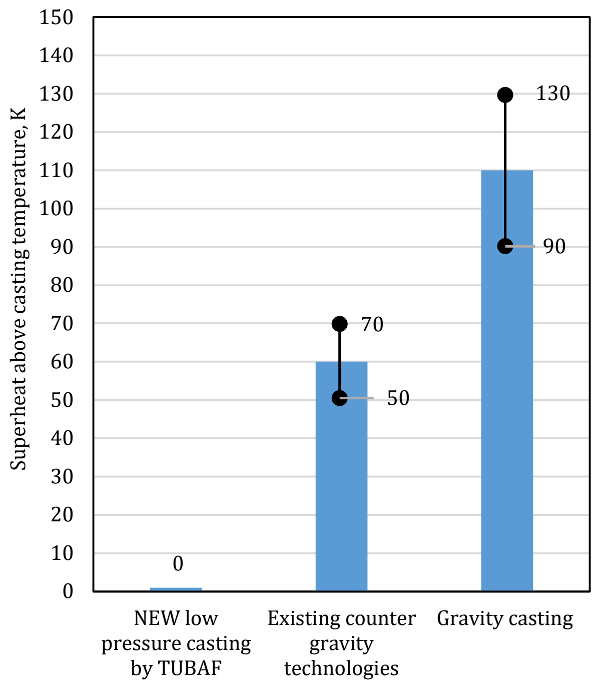


Fig. 4. Needed superheat average and range above casting temperature of different casting technologies

In the following, only the precisely quantifiable effect of the lower necessary superheating should be illustrated. If one compares the newly developed low pressure casting process with the conventional gravity casting process and also assumes a temperature window of ±8 K or ±5 K with the usual tolerance of the tapping temperature, then in total between 90 K and 130 K of superheating temperature can be saved. Modern induction furnaces require approx. 70 kWh of energy per tonne of charge material for a superheat of 100 K. If we again assume a casting weight of 50 kg per 60 s time window, a two-shift operation and the availability and efficiency already mentioned, the daily melt volume is approx. 43.9 tonnes. In this case, 50 kg cast weight in 60 s is also considered realistic for a gravity casting process, although the cycle time per mould is less than 60 s, but less material can be cast per mould due to the realisable volume flows. The daily energy demand, which only arises due to the higher overheating in the gravity casting process compared to the newly developed low pressure casting process, is thus between approximately 2766 kWh and 3995 kWh. Based on an electricity price of only 0.13 €/kWh, the necessary superheating in the gravity casting process alone means an additional daily financial expense of 360 € to 519 €. With 250 working days, the annual additional expenditure can be estimated at around 90,000 € to 130,000 €. Furthermore, as the ecological footprint of products gets more valuable these facts can lead to additional benefits in future.

As can be seen in Table 1, the existing low pressure casting system is rated worse than the gravity casting process in the overall evaluation of energy efficiency, despite the initially described advantages of a lower necessary superheat of 50 K to 70 K. This is due to the fact that the existing systems are induction channel furnaces that are used as holding units. The special feature of these furnaces is the fact that they can only be operated with sump. In addition, the use of special refractory materials significantly extends the life of the wear lining around the channel inductor, because a new lining in these furnace areas is much more expensive than the relining of a crucible induction furnace, which is carried out once a week in most steel foundries. This means that the casting and holding furnaces of the low pressure casting technology currently available on the market are not switched off and have to keep a sump permanently warm. In total, this even consumes more energy compared to the gravity casting process than can be saved through the lower superheating.

3.6. Casting pressure

The casting pressure is rated positively compared to gravity casting for all counter gravity processes. This is mainly due to the fact that it is variable and more reproducible. Whereas in gravity casting it is strongly dependent on the current filling level of the ladle, any tilting movement that may take place and the mould geometry, in the counter gravity casting processes it is determined directly by the controlled pressure above or below the atmospheric pressure. A limitation in the vacuum counter gravity casting process is the fact that a smaller pressure range can be used for mould filling than in the low pressure casting process. The achievable pressure change compared to atmospheric pressure is naturally a maximum of approximately 1000 mbar, whereby it is technically very complex and cost-intensive to achieve such a low absolute pressure. In most cases, it can be assumed that a pressure difference of 650 mbar to 800 mbar can be used for mould filling. This limit can be significantly exceeded with low pressure casting processes. The limiting factors here are primarily the design and associated financial outlay. This effort must be matched by a concrete benefit so that pressure differences above 1500 mbar are meaningful. However, in furnaces with a very large capacity over 6 to, which are used at the same time for casting very large and especially high moulds (height > 1 m), this is technically possible and physically not as limited as in vacuum counter gravity casting processes. The good reproducibility of the casting pressure with the newly developed low pressure casting technology could be proven in an overpressure range of up to 1500 mbar in various pilot plant trials at the Foundry Institute. The following Figure 5 illustrates the percentage differences between the target pressure and the actual pressure in a total of 5 casting tests on different casting days with the same target pressure curve. In this case, the target pressure curve is divided into two sections, which first contain a constant pressure increase over 11 s and then a pressure hold over 14 s.

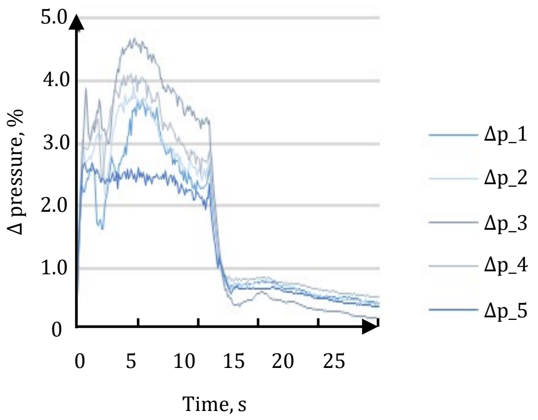


Fig. 5. Casting pressure difference target to current in low pressure casting pilot plant; Δp_1–Δp_5 – casting tests on different casting days with the same target pressure curve

It can be seen that the existing difference between the target and actual pressure occurs mainly shortly after the start of pressurisation. This can be explained by the control times of the valves. Within the first half second after the start of the pressure curve, the pneumatically controlled valves are opened first and thus the desired pressure increase cannot yet be achieved immediately. The actual pressure curve thus lags behind the target pressure curve by about 0.5 s over the entire first section of 11 s. Despite this, there are only deviations of under 5% at any point in this first phase. If one neglects the initial delay of approximately 0.5 s and sets the time zero point of the actual pressure curve when there is a pressure increase in the system, then a more representative picture of the real deviation of the actual from the target pressure curve emerges. The corresponding percentage deviation is shown in Figure 6.

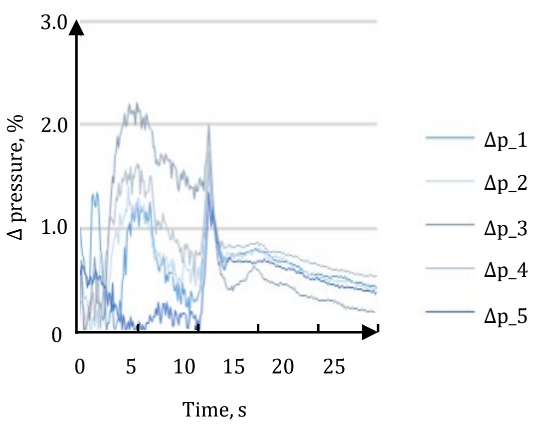


Fig. 6. Casting pressure difference target to current in low pressure casting pilot plant; synchronized; Δp_1–Δp_5 – casting tests on different casting days with the same target pressure curve

It is shown that in the phase of a linear pressure increase, there is only a deviation of approximately 2% between the target and actual pressure curves. In the pressure holding phase, this deviation is further reduced to lower than 1%. At the time of the shift from phase 1 to phase 2 after 11 s, the effect of the valve control can be seen again. The difference between the target and actual pressure curves increases briefly for a short period of time.

For a practical evaluation of the pressure deviations shown, the metallostatic pressure should be used. This results according to Equation (6):

$$p = h \times g \times \rho \tag{6}$$

where:

p – pressure [Pa],
h – height [m],
g – gravitational constant [N/kg],
ρ – density [kg/m^3].

Extensive tests have shown that a maximum pressure deviation of 20 mbar or 2000 Pa can be assumed from one casting process to another. This results in a maximum changed metallostatic pressure height which is calculated as follows:

$$h = \frac{p}{g \times \rho} = \frac{2000\ \text{Pa}}{9.81\ \text{N/kg} \times 6800\ \text{kg/m}^3} = 0.029\ \text{m} \tag{7}$$

If one compares this value with the usual bath level decrease in a stopper ladle, then one will notice that in industrial practice the casting pressure difference during a single casting process is usually greater than that which can be achieved in the low pressure casting process. This is realizable in a process-safe and permanent manner for each casting regardless of the furnace filling level. If one takes into account that the bath level in a stopper ladle often drops by 1 m to 2 m over a complete ladle cycle and thus over the course of approximately 10 to 20 castings, then it becomes clear how precisely the pressure control in the low pressure casting systems works.

These relationships also lead to the extremely good evaluation of the mould filling characteristics, as they result in very reproducible mould filling. Intensive tests on test specimens and real component geometries with the newly developed low pressure casting process have already proven this.

3.7. Feeding effect and casting yield

A general evaluation of the feeding effect compared to gravity casting is relatively difficult, as it depends very much on the component geometry that should be casted and thus to what extent an overpressure can be used for feeding after the mould has been filled completely. Furthermore, the design of the specific casting and gating system plays a very decisive role in this regard. At least the fact that it is possible to realise active feeding leads to the slightly positive evaluation of the two low pressure casting technologies. Since this form of active feeding is not possible with the vacuum counter gravity casting process, the evaluation compared to the gravity casting process is neutral.

Nevertheless, there is enormous potential to increase the casting yield with all counter gravity casting processes. For the two low pressure casting processes, this can be evaluated even better than for the vacuum counter gravity casting process for the last reason mentioned. The greatest potential for optimisation is offered by streamlining the casting and gating system. The flow paths can be kept significantly shorter in a mould designed for the counter gravity casting process. In addition, a larger number of components can usually be cast in one mould because significantly higher melt volume flows can be realised. In this way, the proportional mass of the casting system per component is reduced even further. Investigations with different component geometries have shown that the casting yield can be increased by 15% to 20% when switching from the gravity casting process to a low pressure casting process without extending the cycle time of the casting process per component. This increased casting yield has a large monetary impact, especially for high-alloyed steel castings. The pure material costs of high-alloyed CrNi-steels are usually over 3.50 €/kg and sometimes even exceed 6 €/kg. In concrete application cases, with a raw part weight of 3.8 kg and a material price of 4.75 €/kg, a reduction in manufacturing costs of more than 3.50 € per component could be demonstrated by increasing the casting yield alone, which corresponds to a reduction in the manufacturing costs of the raw part of more than 8%.

3.8. Cycle time

The cycle time for all counter gravity casting processes is neutral compared to gravity casting. Depending on the exact process design and the design of the casting and gating system in the sand mould, both positive and negative effects are possible here. For this reason, no explicit evaluation will be made.

3.9. Costs

The final evaluation of the costs is largely based on all of the previous statements. In addition, especially in the evaluation of asset costs, there is the fact that with the counter gravity casting technologies already available on the market, a further unit is required for melting in addition to the casting unit, whereas with the newly developed low pressure casting process, melting and casting can take place in the same furnace. In the case of the vacuum counter gravity casting process, it should also be mentioned that the overall technical effort required to generate a vacuum in the casting system is greater than that required for casting with overpressure. This fact also leads to higher maintenance and servicing costs, which in particular is the cause of higher costs of operation compared to the low pressure casting processes.

4. SUMMARY

Overall, the higher asset costs, costs of operation, poor availability and other individual factors of the existing counter gravity casting processes leads to higher costs per casted component for the foundry. These could only be compensated by a reduction in the scrap rate due to higher process stability and, in particular, improved mould filling characteristics. However, the extent to which the scrap rate can be reduced in this way is highly dependent on the respective component, the explicit alloy and the quality requirements. For this reason, the technological decision was often made against a counter gravity casting process if this was not explicitly demanded by the customer or if the component could not only be produced using the counter gravity casting process due to its thin walls.

With the newly developed low pressure casting process, which uses a crucible induction furnace in combination with a casting pipe as a melting and casting unit, it is possible for the first time to reduce the manufacturing costs per component to the level of a gravity casting process or even to undercut them. This makes the low-pressure casting process interesting for industrial series production for the first time from an economic point of view. In addition, from a technological point of view, a highly reproducible and controllable process can be achieved. All in all, this leads to more narrowly definable process windows. In this way, the entire melting and casting process can be significantly optimised. For example, the potential is created to cast components with smaller wall thicknesses and to improve the quality or reduce the reject rate. Thus, the overall output can be increased and the costs per part can be reduced even further. In addition, completely new possibilities arise for the production of ultra--thin-walled cast steel components. The enormous variety of steel materials and their good specific properties, in combination with thin-walled and cost-efficient production using the newly developed low-pressure casting process, offer enormous potential for the development of new cast components. A major transformation is currently taking place particular in the automotive industry. New platforms for hybrid and electric vehicles have been developed and demand ever stiffer body structures with simultaneous requirements for weight reduction. In addition, this change also leads to the creation of completely new types of components. The newly developed low-pressure casting process has great potential, both from a technical and an economic point of view, to meet the changing market requirements and to competitively produce new types of high-performance components in best quality as cast components.

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