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CASTING PROCESS OPTIMIZATION BY THE REGRESSION ANALYSIS APPLIED ON THE WEAR RESISTANT PARTS MOLDING

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Preliminary notes

Conducting a comprehensive research of the casting process of wear resistant parts (white hard casting), a significant correlation is established between the technological parameters (temperature, aging time in the mold and coolant flow) and the final product hardness. The fundamental theory of Box-Wilson's gradient method marked the baseline for the foreseen researches. The method defines the coherence of the process parameters, since their dispersion in the examined process is relatively small. Main target of the experiment was a definition of the optimal casting conditions. Therefore the different technological routes are identified and the casting process is modified until the best outcome is achieved. Target function was initially in a hypothesized form, while later on evolved into a consistent form due to the application of experiment-statistics, process optimization and process management based on empirical feedback.

Keywords: *casting, mathematical model, quality management, wear resistance*

Optimizacija procesa lijevanja pomoću regresijske analize primijenjene na kalupljenje dijelova otpornih na habanje

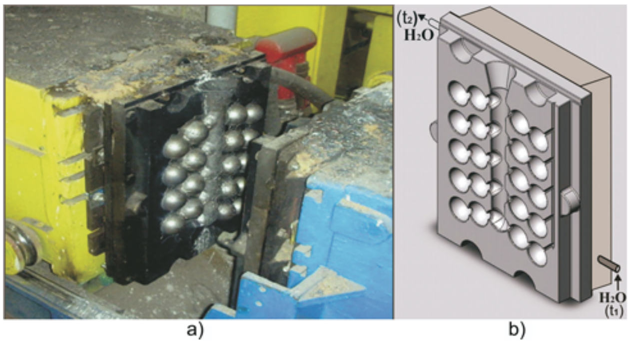
Prethodno priopćenje

Provodeći sveobuhvatno istraživanje procesa lijevanja dijelova otpornih na habanje (lijevanje bijelog željeza), uspostavljena je značajna korelacija između tehnoloških parametara (temperatura, vrijeme starenja u kalupu i protok rashladnog sredstva) i tvrdoće finalnog proizvoda. Osnovna teorija Box-Wilsonove metode gradijenta činila je osnovu za predviđena istraživanja. Ta metoda definira koherentnost parametara procesa budući da je njihova disperzija u ispitivanom procesu relativno mala. Glavni je cilj eksperimenta bila definicija optimalnih uvjeta lijevanja. Stoga su identificirane različite tehnološke rute i modifikacije u procesu lijevanja dok se nije postigao najbolji rezultat. Ciljna je funkcija u početku imala oblik hipoteze, ali je kasnije dobila konzistentan oblik primjenom statističkih podataka dobivenih eksperimentom, optimizacijom procesa i upravljanjem procesom na bazi empirijske povratne veze.

Ključne riječi: *lijevanje, matematički model, upravljanje kvalitetom, otpornost habanju*

1
Introduction

Hard casting is a specific alloy which has the complete carbon content bound into cementite (Fe_3C) or the prevailing content of the carbon is bound into cementite and the minor portion appears in the form of graphite. This is accomplished by the appropriate chemical composition of the casting and faster cooling during the hardening process. Silicon content in hard casting is relatively low and the faster cooling rate prevents the cementite decomposition especially when performed in metal molds. According to the structure of the fracture cross section, two types of hard casting appear: white hard casting and hard-shell casting. White hard casting (white cast iron) is utilized for the items exposed to wear, such as excavator cutting tools, crusher parts, mill-balls (flotation balls), sand blusters, etc.



a) b)

Figure 1 Flotation balls-casting in metal molds: a) released mold shells in the drip caster b) 3D solid model of the mold shell

The purpose of the research is to define the theoretical model for the process management of a drip casting with the low-chromated white cast iron. The casting technology of the flotation balls from low-chromated white cast iron in metal molds (Fig. 1) is researched. The metal molds are water cooled in order to control vital properties of the balls, as well as to cool the mold body. Casting process and its optimization becomes an ultimate move towards the global market requirements and ecological regulations which dictate both increased technical performance and the high economical efficiency for modern foundries. The optimization method developed with this work significantly improves the quality of the molded flotation balls cast in the foundry IK "Guča" SC.

2
Experiment description

The fundamental theory of the Box-Wilson's gradient method is implemented for the baseline of the conducted researches in techno-economical optimization of the process [1, 4, 9]. This method is used to determine the most convenient operating conditions of the process through the identification of optimal technological routes in the casting management process. Target function was initially in a hypothesized form, while later on it evolved into a consistent form due to the application of experiment-statistics [10], process optimization and process management based on an empirical feedback.

Temperature of the casting process is to be kept within a narrow span which corresponds to a chemical composition and the size of the mould. More specifically, a lower casting temperature causes premature solidification in the feeder, which prevents a regular mould forming and reflects on its hollow structure. Too high casting temperature leads to excessive mould shrinkage and thermal shocks. On the other hand an extremely rapid mould cooling causes procreation of inhomogeneous and coarse grained pearlite-carbide structure in the ball body, which significantly reduces its hardness and impact toughness. Therefore it is necessary to provide a well controlled thermal profile of cooling process in order to create a fine grained, spiky pearlite-carbide structure, randomly spread. Such a metallographic structure improves the hardness and the toughness of the product.

2.1
Hardness influence factors

Specified values of the hardness influence factors for the flotation balls (Tab. 1) are obtained from the previous experiments, common foundry practice, references, experience and some specific preliminary researches [2, 3, 5].

Table 1 Hardness influence factors

Factors			
	Casting temperature	Aging time in the mold	Coolant flow
	ϑ /°C	t /s	Q /l/min
Max.	1310	210	35
Average	1280	180	30
Min	1250	150	25

2.2
Matrix of influence factors

The matrix of influence factors in the experiment is shown in Tab. 2 [4]. Other influence factors than quoted, which could also affect the flotation balls hardness have been kept steady: chemical composition of low-chromated white cast iron (flotation balls), temperature of coolant, as well as the balls amount in the mold (20 balls ∅60 in a cluster), Fig. 1. Temperature of the melted low-chromated white cast iron was measured with a submerging pyrometer (Fig. 2). Coolant flow (water) was measured with a precise industrial water-flow-meter (Fig. 3).

Aging period in the mold was controlled with a built-in timer. Samples of the flotation balls were machined prior to hardness measurement (flotation balls ∅60). Hardness was measured according to Rockwell C methodology, at the Zastava Cars SC PC Central Laboratory, meteorological laboratory Kragujevac, approved by the National Auditing Agency.

Figure 2 Temperature measurement

Figure 3 Coolant flow measurement

3
Results overview

Outcome of the experiment, flotation ball hardness for the predefined casting parameters, is shown beneath, Tab. 3.

3.1
Three-factor casting process

Three-factor casting process has been performed in accordance with a full orthogonal plan $2^k = 2^3$, having a triple repetition at the central point of a multifactor orthogonal diagram ($\vartheta = 1280$ °C, $t = 180$ s, $Q = 30$ l/min). The flotation ball hardness Rockwell C (HRC) is represented by the equation (1), [3, 4, 7].

$$HRC = D \cdot \vartheta^{p} t^{q} Q^{r} \tag{1}$$

Table 2 Matrix of correlation

No.	Coded influence factors				Actual hardness - measured in cross section		Calculated values	Difference of actual to calculated values
	x_0	x_1	x_2	x_3	HRC	$y_i(\ln HRC)$	$\hat{y}_i$	$(y_i - \hat{y}_i)^2$
1	+1	–1	–1	–1	54,66	4,0011	4,0083	0,00005184
2	+1	+1	–1	–1	56,66	4,0371	4,0157	0,00045796
3	+1	–1	+1	–1	55,33	4,0133	4,0055	0,00006084
4	+1	+1	+1	–1	54,66	4,0011	4,0129	0,00013924
5	+1	–1	–1	+1	53,83	3,9858	3,9903	0,00002025
6	+1	+1	–1	+1	54,50	3,9982	3,9977	0,00000025
7	+1	–1	+1	+1	54,66	4,0011	3,9875	0,00018496
8	+1	+1	+1	+1	54,33	3,9951	3,9999	0,00000004
9	+1	0	0	0	54,00	3,9890	$y_0 = 3{,}9951$	$\Sigma = 0{,}00091538$
10	+1	0	0	0	54,00	3,9890		
11	+1	0	0	0	55,00	4,0073		
Key: x_0 – dummy factor, x_1 – coded temp , x_2 – coded aging time , x_3 – coded coolant flow								

Table 3 Table of results

No.	Influence factors	HRC
01	1250 °C; 150 s; 25 l/min	54,66
02	1310 °C; 150 s; 25 l/min	56,66
03	1250 °C; 210 s; 25 l/min	55,33
04	1310 °C; 210 s; 25 l/min	54,66
05	1250 °C; 150 s; 35 l/min	53,83
06	1310 °C; 150 s; 35 l/min	54,50
07	1250 °C; 210 s; 35 l/min	54,66
08	1310 °C; 210 s; 35 l/min	54,33
09	1280 °C; 180 s; 35 l/min	54,00

D – is the rectification coefficient, ϑ (°C) – is the temperature in casting , Q (l/min) – coolant flow and t (s) – the aging period of the samples in the mold. Natural logarithm of the equation (1) yields the first order model expressed by the equation (2).

$$\hat{y} = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3. \qquad (2)$$

Where:

$$\hat{y} = \ln HRC,$$
$$b_0 = \ln D,\ x_1 = \ln\vartheta,\ x_2 = \ln t,\ x_3 = \ln Q,\ b_1 = p,$$
$$b_2 = q,\ b_3 = r.$$

By coding the independent variables x_1, x_2, x_3 with three successive integer values (–1, 0, +1) the mechanism of determining coefficients, b_i (i = 0, 1, 2, 3) is radically simplified with transformation formula (3).

$$x_i = 1 + 2\frac{\ln x_i - \ln x_{i\max}}{\ln x_{i\max} - \ln x_{i\min}}, i = 1, 2, 3. \qquad (3)$$

The values of the regression coefficients b_i are obtained from the equation (4).

$$b_i = \frac{1}{N}\sum_{u=1}^{N} x_{iu} y_u,\ i = 0;\ \ N = 2^k + n_0;\ \ i = 1, 2, 3; \qquad (4)$$

$$N = 2^k.$$

Combining results from Tab. 2, with the ones from equation (4) the regression coefficients become: b_0 = 4,0016, b_1 = 0,0037, b_2 = –0,0014, b_3 = –0,0090. Further on, the regression model (2) established in the coded coordinates, converts into the form expressed by (5).

$$\hat{y} = 4{,}0016 + 0{,}0037 \cdot x_1 - 0{,}0014 \cdot x_2 - 0{,}009 \cdot x_3. \qquad (5)$$

Regression model (5) for the specified process conditions, is then transmitted by the (6) and (7) into 3D coordinates (8) and (9).

$$\ln D = \sum_{i=0}^{3} b_i - 2\left[\frac{b_1 \ln\vartheta_{\max}}{\ln\frac{\vartheta_{\max}}{\vartheta_{\min}}} + \frac{b_2 \ln t_{\max}}{\ln\frac{t_{\max}}{t_{\min}}} + \frac{b_3 \ln Q_{\max}}{\ln\frac{Q_{\max}}{Q_{\min}}}\right] \qquad (6)$$

$$p = \frac{2b_1}{\ln\frac{\vartheta_{\max}}{\vartheta_{\min}}};\quad q = \frac{2b_2}{\ln\frac{t_{\max}}{t_{\min}}};\quad r = \frac{2b_3}{\ln\frac{Q_{\max}}{Q_{\min}}}; \qquad (7)$$

$$\ln HRC = \ln D + p\ln\vartheta + q\ln t + r\ln Q \qquad (8)$$

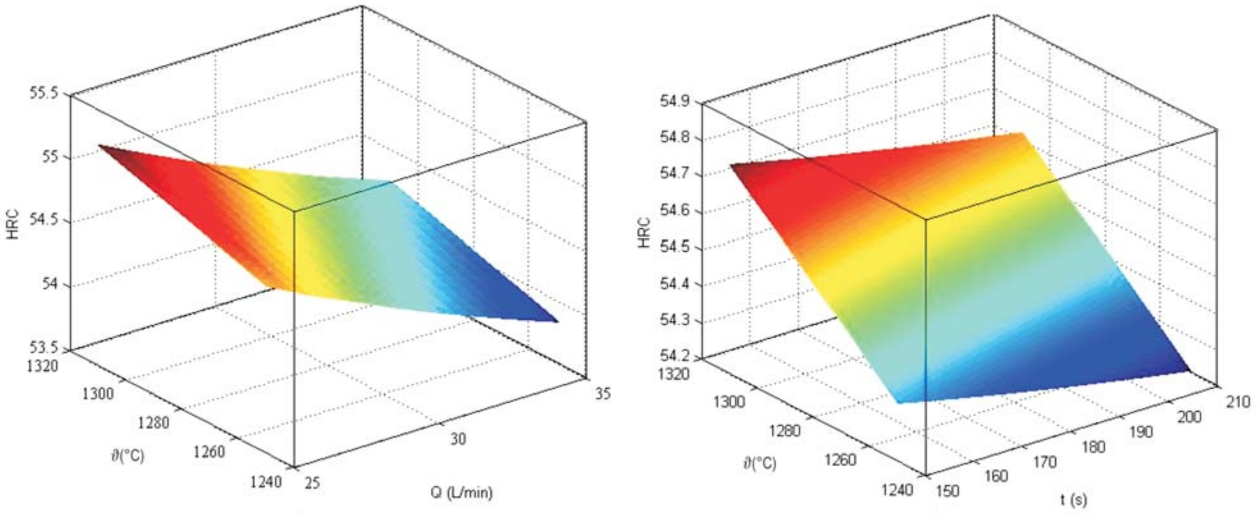
Further on inverse of natural logarithm yields:

$$HRC = 21{,}254 \cdot \vartheta^{0{,}161} t^{-0{,}0086} Q^{-0{,}0538}. \qquad (9)$$

Calculated ball hardness is obtained from the formula (9) engaging the variables specified in the Tab. 3:

$$HRC_1 = 53{,}97,\ HRC_2 = 54{,}37,\ HRC_3 = 53{,}807,$$
$$HRC_4 = 54{,}23,\ HRC_5 = 56{,}057,\ HRC_6 = 56{,}428,$$
$$HRC_7 = 55{,}89,\ HRC_8 = 56{,}32,\ HRC_9 = 56{,}51.$$

Fig. 4 illustrates a schematic correlation between the three input casting factors: temperature of the melted low-chrome white cast iron (ϑ), aging time in the mold (t), coolant flow (Q) and the product hardness (HRC). MATLAB software package [8] is deployed to build the 3D image.



a) b)

Figure 4 Correlation of casting parameters and the product hardness: a) invariant-aging time in mold b) invariant-coolant flow

3.2
Result dispersion

Dispersion of the results in this experiment depends on: the overall experiment concept, ambient conditions, measurement accuracy, post event data management, use of former results etc. Calculation of the experiment deviation $s^2(y)$, is related to the total number of (N) points, where the measurement is repeated n_0 times (n_0 = 3) at the central point. The deviation s of the results is calculated in accordance with the equation (10).

$$s^2(y) = s_E^2 = \frac{S_E}{f_E} = \frac{1}{n_0-1}\sum_{i=1}^{n_0}(y_{0i}-\bar{y}_0)^2. \qquad (10)$$

Where:

$$\bar{y}_0 = \frac{1}{n_0}\sum_{i=1}^{n_0} y_{0i} \qquad (11)$$

S_E – is the sum of the difference squares at the central point of the 3D plane:

$$S_E = \sum_{i=1}^{n_0}(y_{0i}-\bar{y}_0)^2 \qquad (12)$$

f_E – degree of freedom of the variable difference:

$$f_E = n_0 - 1. \qquad (13)$$

In this experiment calculated values are as follows:

$$\bar{y}_0 = 3{,}9951;\ s^2(y) = s_E^2 = 0{,}00011163;$$
$$S_E = 0{,}00022326;\ f_E = 3-1 = 2.$$

3.3
Model conformity verification

Conformity verification of the mathematical model (5), i.e. (9) is a crucial step of the process modeling. In general, the conformity verification involves comparison of the experiment results dispersion related to the regression line s_R^2, more specifically the dispersion at the points of multifactor space s_E^2 in accordance with Fisher's criterion (14), [1].

$$F_r = \frac{s_R^2}{s_E^2}. \qquad (14)$$

Where:
s_R^2 – is the dispersion of mean values of the experimental results related to the regression line and expressed by the equation (15):

$$s_R^2 = \frac{S_R}{f_R} \qquad (15)$$

S_R – residual sum:

$$S_R = \sum_{i=1}^{N=8}(y_i-\hat{y}_i)^2 \qquad (16)$$

f_R – degree of freedom of residual force:

$$f_R = N-k-1. \qquad (17)$$

For this experiment the calculated values are

$$S_R = 0{,}00093906;\ f_R = 13-3-1 = 7;$$
$$s_R^2 = 0{,}0001328;\ F_r = 1{,}172.$$

According to the bibliography [1] when taking $k_1 = f_R$ = 7, $k_2 = f_E$ =2 and the probability factor α = 95 %, the permitted value of dispersion is F_t = 19,35. Since the calculated value of F_r = 1,172 < F_t = 19,35 thus the mathematical model given by the equation (5), i.e. in the natural coordinates by the equation (9), describes the casting process properly.

4
Metallographic analysis for the Quality Assessment

Metallographic analysis has been performed on the surface of a ball cross section (thickness of the removed calotte is 5÷10 mm). A usual sample preparation (grinding, polishing, and abrasion) is conducted prior to microscoping. The polished surface is etched with the 10 % nitric acid (HNO_3). The microstructure shots have been made with an optical microscope (magnifying factor 16÷2000) POLYVAR-MET, REICHERT, equipped with the Q500MC, Leica picture analyzer. Focused points of the cross section are located 2,5 mm and 10 mm far from the outer contour, as well as in the very centre of the cross section. Metallographic analysis was implemented both on samples produced with the conventional technology and newly developed one.

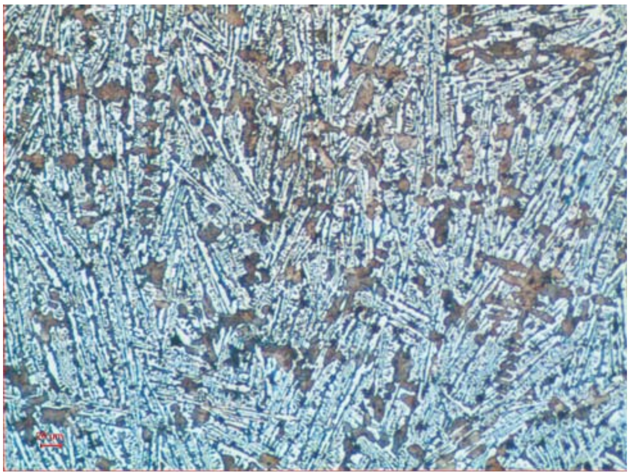


Figure 5 Microstructure - conventional technology (×100)

Fig. 5 shows the microstructure in the cross section central zone, 100× magnified (conventional technology: casting temperature ϑ = 1300 °C, aging time in the mold t = 180 s, free coolant flow). Average hardness in the cross section is 53 HRC. Fig. 5 reveals the presence of pearlite in the microstructure (generated by the transform of the primary isolated austenite of dendrite morphology) and the carbide $(FeCr)_3C$. The structure $(FeCr)_3C$ is rather coarse and chaotic. Mass reduction of the flotation balls in the exploitation is 650 g/t (ball grams per a ton of treated ore).

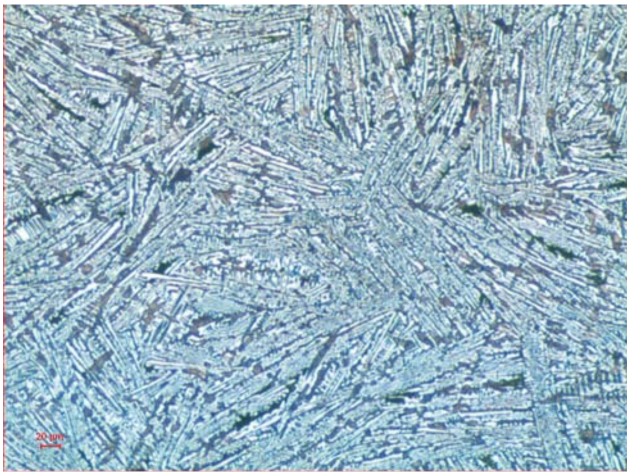


Figure 6 Microstructure - novice technology (×100)

Fig. 6 shows microstructure in the cross section, central zone 100× magnified. Average hardness in the cross section is 57 HRC. The ball microstructure is again pearlite-carbid, but evenly spread and rather small-grained. Such a spiky and randomly oriented morphology of the excreted phases, improves overall hardness and positively affects impact toughness. The set of performed metallographic analyses of the two different kinds of flotation balls ∅60, showed that their structure is well influenced by the process profile and that the innovative methodology certainly provides better exploitation properties. Mass reduction of such flotation balls in the exploitation is 540 g/t (ball grams per a ton of treated ore), which is 17 % better than with conventionally produced balls. Finally, an important remark for this class of materials (low Cr %): "The steeper the cooling rate, the finer the metallographic structure and greater the sample strength, accordingly".

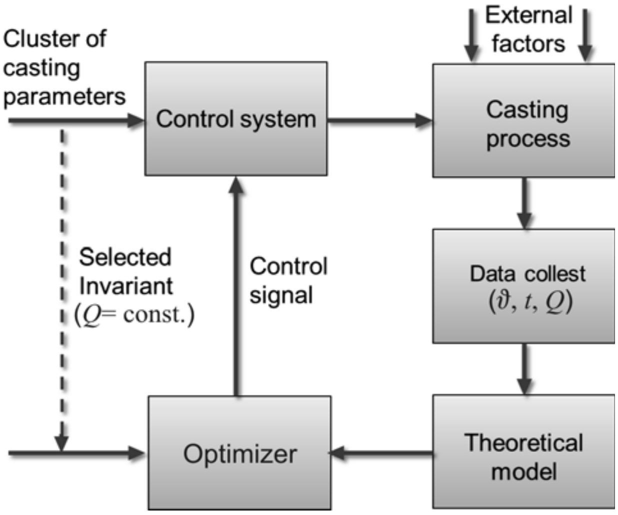


Figure 7 Casting process flow chart

5 Flow chart of the casting process

Theoretical model of the process control comprises all necessary data needed to define the structure of an adaptive system [6]. Focus of the optimization is kept on the following outcomes: overall productivity, dimensional accuracy, achieved quality and production costs. Such an adaptive control system is capable of modifying the algorithm through the process performance. Usually the control system shifts the steering when the process variables overstep predicted values, mostly affected by the external factors. The example of such a case is the casting temperature of flotation balls which varies from 1450 °C (in electro-furnace) to 1250 °C (in the moment of pouring) and the optimum temperature is around 1300 °C. The flow chart of the overall casting control is illustrated by Fig. 7.

6 Conclusion

The process of copper ore pretreatment (flotation) is preferably oriented on application of low chromate balls (2,2÷2,6) % Cr, cast in metal molds with intensive water cooling to provide a beneficial recrystallization. This is a superior technology compared with other flotation techniques.

Regular daily production of flotation balls exceeds 30t, which is usually performed with the cast temperature fluctuation in the range (1250÷1310 °C), instead of recommended (1300 ± 10) °C. In order to provide good mechanical properties of the product, besides the casting temperature it is necessary to control other process parameters: aging time in the tool and coolant flow. Fortunately, if the latter two influential parameters (aging time in metal moulds and coolant flow) are in the prescribed range, the ball metallographic structure becomes smooth, small grained, pearlite-carbid with spiky and randomly oriented morphology, which significantly improves its mechanical properties. The most valuable contribution of the conducted researches is the correlation (9), established between the ball hardness Rockwell-C (HRC) and the process parameters, casting temperature ϑ (°C), coolant flow Q (l/min) and the aging time in the tool t (s), for the flotation balls ∅60 (specifically: chemical composition: C = 3,4÷3,7 %, Si = 0,6÷0,8 %, Cr = 2,3÷2,6 %, P_{max} = 0,1 %, S_{max}=0,1%). Regarding the results of performed metallographic analysis, the functional correlation (9) can be successfully used for the active control of the ball hardness in the low-chromated white iron casting process.

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