Archives of Materials Science and Engineering
Volume 58
Issue 2
December 2012
Pages 193-198
International Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering

Modelling of crystallizer wear

J. David*, P. Švec, R. Frischer
Department of Automation and computing in Metallurgy, Vysoká Škola Báňská -
Technical Univerzity of Ostrava, 17. listopadu 15, Ostrava- Poruba, 708 00, Czech Republic
* Corresponding e-mail address: j.david@vsb.cz

Received 21.10.2012; published in revised form 01.12.2012

ABSTRACT

Purpose: In this paper will be described an analysis of control problems and technical lifetime modeling of continuous casting device crystallizers. A full exploitation of continuous casting equipment (CCE) advantages can only be achieved through a control system that minimizes all undesirable effects on the technological process. Some of the undesirable effects influencing the CCE process effectiveness are the failures and service interruptions. The failures and service interruptions are caused by a number of factors, impacts and processes that effect and run directly on the equipment in its individual parts during its operation.

Design/methodology/approach: This problem was solved by connection of dependability theory and artificial neural networks.

Findings: A prediction of crystallizer's desk's wear model was created on the basis of artificial neural networks and analytics diagnostics.

Research limitations/implications: The limitations are given by operational data quantity. These limitations are for learning process and model adaptability.

Practical implications: These problems are solved with cooperation with regional metallurgical companies. Gained results will be applied into the operational conditions.

Originality/value: Signification consists of dependability theory and artificial neural networks, when solving a prediction model of crystallizers wear.

Keywords: Crystallizer; Wear; Modelling; Lifetime; Artificial neural networks

Reference to this paper should be given in the following way:

J. David, P. Švec, R. Frischer, Modelling of crystallizer wear, Archives of Materials Science and Engineering 58/2 (2012) 193-198.

MATERIALS MANUFACTURING AND PROCESSING

1. Objects lifetime

The technological systems service life control includes the process and its control when we determine the period of time during which the equipment or its parts are able to perform the required function under given conditions of use and maintenance up to the moment when the limiting state has been achieved. When dealing with this problem it is necessary to be aware of the fact that the meaning of service life term varies in various stages of equipment life cycle therefore we must distinguish the terms as follows:

- Planned technical life - the period of time determined by the designer, during which the equipment has to be able to perform safely and reliably its function; all economic evaluations and as a rule also the permitting procedures are related to the planned technical life (In principle the planned technical life is shorter than the rated technical life of the equipment);
- Rated technical life - the minimum period of time during which the equipment or its parts must be able to perform safely and reliably their functions under given conditions; this time is determined by means of calculation methods;
- Technical life - the period of time on the expiry of which the limiting state occurs (the technical life is always longer than the rated technical life);

- The total life - the maximum achievable service life of equipment that is terminated by the final retirement of the equipment based on the limiting state;
- The residual life - the period of time during which the technology(or the equipment) can be operated with the required reliability; it is the time left until the technical life or the total life of the equipment have been reached.
- Limiting state - the technical state of the equipment during which the further use of equipment must be interrupted due to an irremovable infringement of safety requirements, irremovably exceeded limits set for parameters, irremovable decrease of operation effectiveness below the admissible level or due to an overhaul execution.

The graphical interpretation of above terms is shown in (Fig. 1).

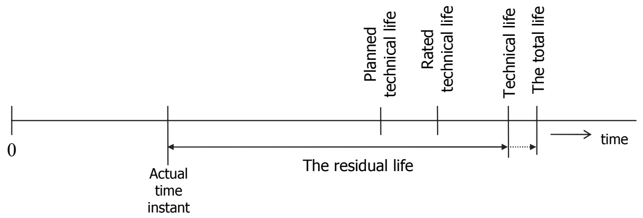


Fig. 1. Graphical interpretation of lifetime terms

The crystallizers lifetime is generally predicted by amount of cast steel in given crystallizes, by total steel weight or by count of passed casts [3].

2. Crystallizers wear

The crystallizer is one part the CCE that significantly influences the PLP quality both in view of the internal structure and the surface purity and the dimensional accuracy. The crystallizer service life is influenced first of all by its wear. The physical mechanism of crystallizer wear can be described as follows [4]:

If the surfaces of two functional surfaces (liquid steel or slightly solidified blank's crust and the crystallizer walls (see Fig. 2) by virtue of the self-weight of steel/blank or the oscillatory mechanism there will be the first contact, theoretically in three points. In these points the real surface pressure is as big as to cause the plastic deformation and parts of surface breaking off (this all in microscopic dimensions). Consequently other places on the parts surface are contacted. On these parts the same processes are running as long as the real contact surface has achieved the level when the real surface pressure does not induce any other deformations. Obviously the achievement of this equilibrium state depends on more factors. For a better description of crystallizer surface wear mechanism it is possible to base it on a general model of the metal polished component surface layer (see Fig. 3) [1].

When nearing the surfaces the integrity of the adsorption layer and the oxide layer gets destroyed and consequently the surfaces get into the metallic contact. This results in micro-joints formation. When they are subsequently destroyed due to the relative movement of surfaces the metallic components become separated and the surface material gets displaced. The intensity of this process depends on many factors and the most important of them are as follows:

- The kind and the characteristics of mutually acting surfaces of bodies;
- The presence and characteristics of the medium between the surfaces;
- The characteristics of a relative motion of surfaces (direction, speed, their time changes).
- Load (the size of acting forces, their time changes).

When applying this principal model of wear to the crystallizer it is necessary to supplement the above factors by the effect of process temperature factors.

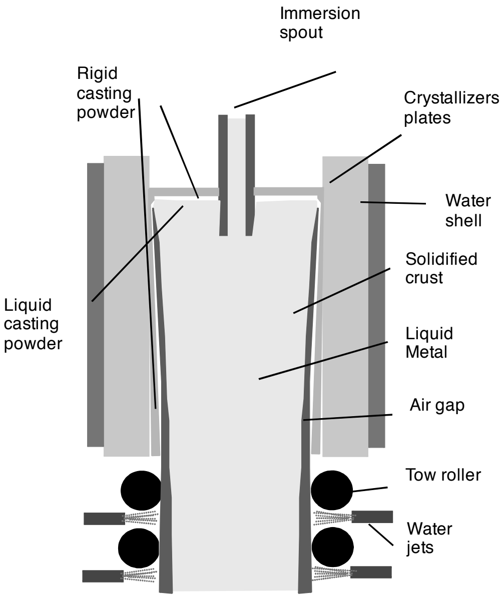


Fig. 2. Scheme of the system: crystallizer - metal

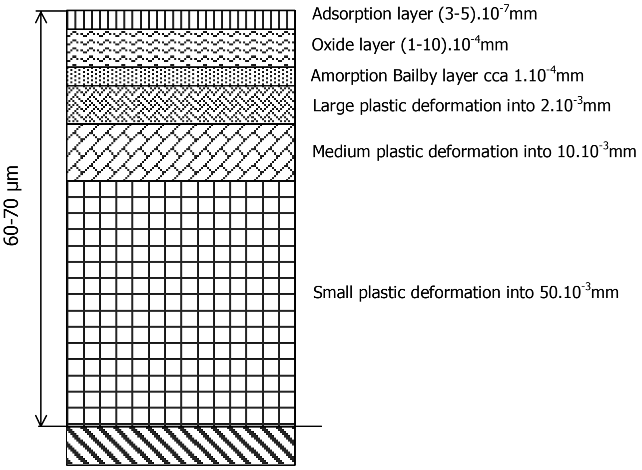


Fig. 3. Schematic cut through the polished surface [2]

3. Modelling of the crystallizer wear

3.1. General base of solution

When designing a solution the subsequent a priori knowledge was used.

- Generally it is accepted, that low profile crystallizers attend to quicker wear due to higher casting speeds.
- Also bent crystallizers has a lower lifetime, which is due to mostly eccentric impact of casting flow into the crystallizer and due to higher mechanical abrasion in lower crystallizers levels.
- Crystallizers with lower profiles distort it selves less than crystallizers with large profiles. Crystallizers with rectangle profile are distorted less then crystallizers with square profile.
- If in continuous casting device is wear greater than 1.5 to 2.0 mm in lower level and by block 0.7mm, in dependence on assortment come in to corner breach and so non qualitative products.
- In lower crystallizers levels the low temperatures and pressure don't let the same conditions when hydrodynamic pasting is involved. In present time we are not able to make perfect image about slag behaviour in this area. In some places attend to dry friction between solid materials. When the copper surface of the crystallizer smoother then surface of solidified steel crust, then it is very probable, that small pieces of slag proceed with the steel in its digressive movement. Before the material get out from crystallizer, its surfaces temperature can come down as low as the slug is acting as a solid material even in the border between liquid and solid stage. On the boundary of solid slug and crystallizers copper surface attend to erosion of copper surface.
- The time to replace crystallizer is deduced from its inner surface or from clearances or geometry of desks.

The operation experience enables us to define following effects impacting the crystallizer service life and the possibilities to influence them during the casting process:

- The properties and the quality of crystallizer material - these properties are explicitly given by the manufacturer of the crystallizer, therefore they cannot be influenced during the casting process.
- The shape and size of the continuously cast blank (only PLP hereinafter) - these parameters are important for calculation of the cast steel mass; the parameters are given by the type of crystallizer, they cannot be influenced during the casting process.
- The way of cooling - it can be influenced, but the way of cooling is given by the technological parameters and is controlled with regard to the casting process technological effectiveness, not in view of crystallizer wear,
- The casting speed - it can be influenced during the casting process, but the same argument as at the way of cooling applies,
- The operational effects (inaccurate centering of immersion nozzles related to the metallurgical axis, casting in a turbulent flow, casting with too low temperature or with a too high aluminium fraction in steel) - some of these impacts can be influenced, but in general there are also preferred the technological and not only the maintenance aspects.

The above facts show that the crystallizer service life maximization is given by mutual combination of construction-technical, operational and organizational parameters that always are related to the concrete equipment [7,8].

3.2. Development of the wear model

The main assumption of quality production (conducted in continuous steel casting devices) is perfect thermal service of the crystallizer. Blanks defects shown in (Fig. 4): uneven chemical composition, inner and outer cracks, surface defects like sealed casting powder, longitudinal cracks in casting crust, excessive oscillating crease, shape defects and so on, have their own main reason in crystallizer.

Especially undesirable are cracks in casting crust caused by ferrostatic pressure, temperature stress, other friction in the crystallizer, and other mechanical stresses that can lead to rupture and break of the crust.

Thermal stress in the blanks crust is caused by the uneven shrinking and by unbalanced intensive cooling. Dangerous is also the influence of crystallizers shape changes, induced by thermal and mechanical stress, which lead to the reduction of the heat dissipation because of excessive gaps between the casting crust and the wall of the crystallizer.

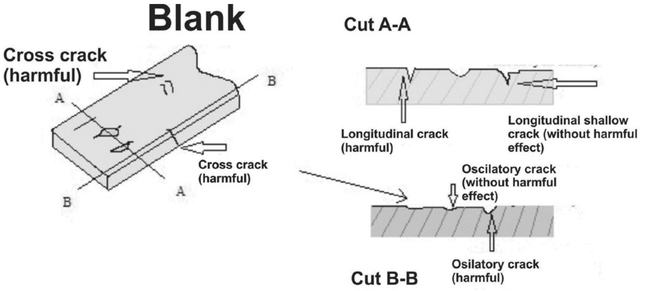


Fig. 4. Sorts of blanks defects

Outbreak is a situation, when a blanks crust crack and liquid metal flow directly from the faulty blank and production must be stopped immediately, which is always associated with relatively high economic losses.

The production quality and production safety from the view of the outbreaks is related to casting technology and also to the construction and adjustment of the casting machine. Both aspects are still subject of the frequent development and improvement. The complexity of processes in continuous steel casting devices is almost impossible to generalize and transfer results from one device to another, even on the same casting device (crystallizer). There are quite different conditions when casting different formats or casting from different steel grades.

The modern trend of increasing casting speeds puts high demands on the crystallizers. The dimensional stability is required, wear resistance and high thermal conductivity. Crystallizer’s ingot is exposed to extreme cyclical, thermal and mechanical stress. In crystallizers ingot is a high temperature difference between outer and inner surface, which is due to the large heat flux density. This creates thermal stress and plastic deformation, which are undesirable in terms of operation. Crystallizers are scrapped basically for two reasons, due to loss of taper wear, and also due to permanent deformation of the crystallizer's wall. The greatest distortions are in surface of the liquid steel and closely below it (Fig. 5).

Experimental research of crystallizer is complex because of the high temperatures and the danger arising from the presence of liquid steel in close proximity to cooling water. Construction equipment adjustments before experiments are costly and can delay production. Experimental research must always take place in conjunction with production company and experimental workplace, which must conform to the priorities of production. In addition to experimental research has its irreplaceable position also mathematical modelling (finite element method, etc.).

The material which is intended for the production of crystallizers is copper, usually a small amount of alloy additives in it, particularly for increasing the surface hardness and wear resistance, also is achieved increasing of recrystallization temperature by simultaneously increasing the recrystallization temperature. Alloying elements are most often W, Ag, Cr, Zr, Co and Be.

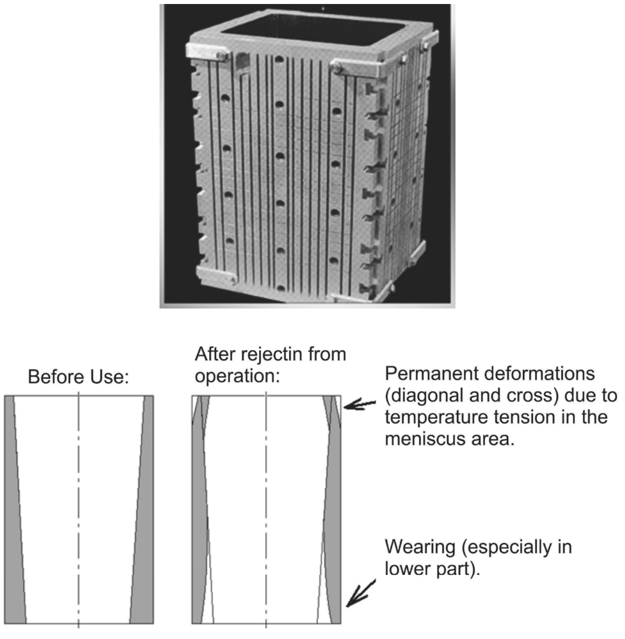


Fig. 5. Wearing of the crystallizer

Effect of alloying additives on the material thermal expansion coefficient is minimal. From the above it follows that the solution of the problem of plastic deformation of crystallizers wall is not only in material selection of the crystallizers desks. The technical solution is a very challenging interdisciplinary problem, which includes disciplines like construction, elasticity / rigidity, thermal engineering, material engineering, experimental methods and numerical methods [5,6].

3.3. Reliability analysis of the plate crystallizers

The emergence of the object limit state is caused by many factors, influences and processes that operate and run directly on the object to its individual parts, in its operation. These effects result in changes in the properties of working surfaces of the object and its parts, and are the primary manifestations of the technical limit state, which affect both the efficiency of the process and also the life of the object. In principle, the threshold condition given by the sum of individual states over the technical life of the object.

From the view of reliability theory can be crystallizer considered as non-renewal object. The first step of solving is the statistical and probabilistic analysis of the technical life of crystallizers. In the frame of this analysis 23 crystallizers was investigated upon which many measurements during its lifetime was made (device MKL 100/420 DASFOS Company, PLC.).

Table 1.
Statistical parameters for solution

Middle smelting count through the technical lifetime of the crystallizers	842.28 smelts
Selective standard deviation	568.67 smelts
Selective dispersion	323396.77 smelts
Variation coefficient	0.675162648
Middle time of models technical lifetime	892.47 smelts

The value of variation coefficient confirms a priori assumptions that the mechanism of the limit state of the crystallizer is caused by wearing of the material. The value of variation coefficient using (Tab. 1.) shows that the random variable will have a normal probability distribution, which further demonstrates the histogram. For solution versatility will not be used normal probability distribution of random variables, but the Weibull probability distribution of random variables, which allows an approximation of a normal distribution with its parameters. We can assume that the calculated variation coefficient will be the value of the Weibull parameter of probability distribution close to the value of the 6 [4].

Weibull disposal probability parameters can be obtained from equations:

$$\frac{\sum_{i=1}^{n} t_i^{\overline{m}} \cdot \ln(t_i)}{\sum_{i=1}^{n} t_i^{\overline{m}}} - \frac{1}{n} \cdot \sum_{i=1}^{n} \ln(t_i) - \frac{1}{\overline{m}} = 0 \tag{1}$$

$$\hat{\lambda} = \frac{n}{\sum_{\forall i} t_i^{\overline{m}}} \tag{2}$$

where

$\overline{m}$ is a point estimation of the Weibull disposal shape,

$\hat{\lambda}$ - a point estimation Weibull scale,

n - number of observation,

t_i - the value of the i-th observation of random quantity t.

By the numerical solution: follows parameters of Weibull disposal were extracted.

- The m parameter 1.324,
- The reciprocal value of the scale parameter 0.000121.

Substituting these values into the relationship (3) we can obtain Weibull distribution function running.

$$F(t) = 1 - e^{-\frac{t^m}{t_0}} = 1 - e^{-\lambda \cdot t^m} . \qquad (3)$$

Distribution function thus obtained was compared with the empirical distribution function obtained from the measured values of the technical life of the crystallizer (Fig. 6) and were performed validation of the distribution function obtained using the Kolmogorov-Smirnov test for a single selection. The test confirmed on the significance level of 0.01 and 0.05, that the distribution function obtained with Weibull probability distribution describes the measured data of the technical life of crystallizer.

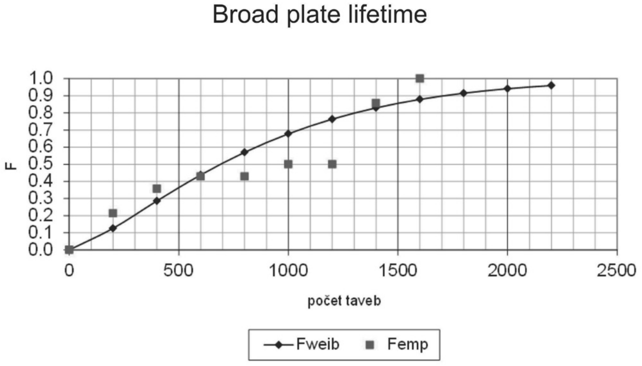


Fig. 6. Comparison of measured data to obtained distributive function

Results of the analysis imply that in many of the crystallizers was not reached even the average technical lifetime. The causes of this condition can be found in the following reasons:

- Human factor.
- The crystallizer is extremely stress by influence of one the above mentioned effects or by incidence of the more effects together and that lead to its higher abrasion and to shortening its technical lifetime.

3.4. Crystallizers wariness model

When creating a crystallizers wear model experimental data from operational monitoring of technological parameters of casting process were used. These parameters were used as inputs and were analysed. The aim of these analyses was to determine the parameters that affect the wear of the crystallizer. As an output parameter was the probability of achieving the ultimate limit state, assuming Weibull distribution. Analyses such as the method of decision trees, sensitivity analysis, regression analysis and the other were set 11 of input parameters (chemical elements composition, overheat temperature, casting speed, ...). These parameters were then inserted into the STATISTICA software that created the desired topology for the network parameters. Network topology was 11-12-1. The network worked with 96% success rate. The results are processed by the network in (Tab. 2). The success of the network is shown in (Fig. 7) [8].

Table 2.
Artificial neural network results

	Sample	F Weib Model (Output (target))	F Weib Model - Output variable (5MLP (VVPS) 11-12-1)	F Weib Model - Residuum (5MLP (VVPS) 11-12-1)
1	Training	0.079968	0.128681	-0.048713
2	Training	0.191384	0.221610	-0.030226
3	Training	0.232824	0.213854	0.018970
4	Training	0.328564	0.264318	0.064246
5	Training	0.417143	0.397885	0.019257
6	Validating	0.480952	0.639500	-0.158547
7	Training	0.566673	0.576226	-0.009553
8	Training	0.648586	0,711206	-0.062620
9	Training	0.732404	0.709140	0.023264
10	Training	0.736214	0.768032	-0.031818
11	Training	0.809067	0.802778	0.006289
12	Training	0.887619	0.880580	0.007039
13	Training	0.903810	0.884325	0.019484

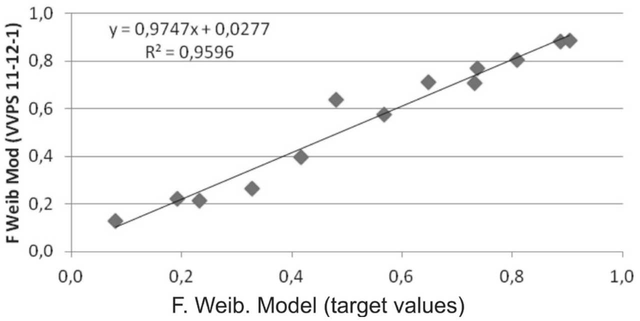
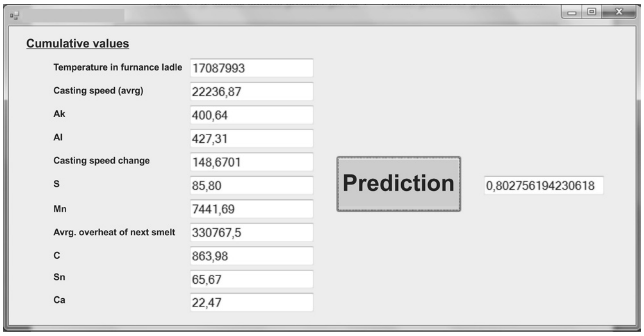


Fig. 7. Dependence of the output target value on outputs of the neural network

3.5. Prediction model

Based on the results of STATISTICA software an application for the assessment of crystallizer wear was developed. The application was created in the software Microsoft Visual Studio 2010. In this environment executable programs under MS Windows OS are create. The user software has a code produced by artificial neural network for crystallizer wear. The code is generated in C ++ by software STATISTICA. The generated code has to be properly adjusted before implementation in the user environment. This modification involved deletion part of the code and the appropriate adjustment to the code for user interface (see Fig. 8).



Cumulative values

Temperature in furnance ladle	17087993
Casting speed (avrg)	22236,87
Ak	400,64
Al	427,31
Casting speed change	148,6701
S	85,80
Mn	7441,69
Avrg. overheat of next smelt	330767,5
C	863,98
Sn	65,67
Ca	22,47

0,802756194230618

Fig. 8. Evaluation of crystallizer wear - user interface screen

4. Conclusions

The Department of Automation and Computing in metallurgy, VSB-TU Ostrava has long dealt with the challenge of life of technical systems. In the frame of this solution it is solved an area of metallurgical objects life. One of these objects is the crystallizer of the continuous steel casting device. The current solution results shows that is necessary to use knowledge, not based only on objective qualitative knowledge, so then knowledge subjective and heuristics. The results are the constructions processes using effective model structures, the same principles which utilize human experts. This approach to solving complex systems leading to deployment of systems based on artificial intelligence methods.

The results achieved on the proposed system for dealing with crystallizer wear, shows, that the issue can be addressed using these systems. The result is a software application to assess the state of crystallizer parameters for the specified technology. Thus conceived application can be used to control maintenance with regard to the state assessed property, and for the operational management of the process of continuous steel casting devices with regard to the quality process.

Acknowledgements

This article was created with help of financial support of ministry of industry and trade of Czech Republic: solution of grant project TIP ev. č. FR-TI1/319 „Vývoj nových progresivních nástrojů a systémů podpory řízení spolehlivostí primárního chlazení na bramovém zařízení plynulého odlévání ocelí pro zvyšování kvality náročných plochých výrobků“ and in terms of project SP2012/42.

References

[1] J. David, M. Heger, M. Vrožina, L. Válek, Visualisation of data fields, Archives of Metalurgy and Materials 55/3 (2010) 795-801.

[2] J. David, R. Frischer, Development of new progressive tools and systems for quality improving of dependable flat products on slab device of continuous casting, Acta Metallurgica Slovaca 1 (2010) 162-166.

[3] M. Vrožina, et al., Usage of knowledge systems in maintenance control of metallurgical devices with help of continuous diagnostics into the solution, VŠB-TU Ostrava, 2004, Final report of grant project 106/05/2596 for period 2005-2007, VŠB-TU Ostrava, 2008.

[4] J. David, et al., Stage 2 - Identification of diagnostics quantities and development of diagnostics system, Report about stage solving in TIP program, VŠB-TU Ostrava, 2010/12.

[5] A. Carpinteri, Critical defect size distributions in concrete structures detected by the acoustic emission technique, Meccanica 43 (2008) 349-363.

[6] V. Volkovas, J. Dulevicius, Acoustic, emission used for detection of crack generation in propellers of turbine-pump units, Russian Journal of Nondestructive Testing 42/4 (2006) 248-254.

[7] R. Lenort, A. Samolejová, Analysis and identification of floating capacity bottlenecks in metallurgical production, Metalurgija 46/1 (2007) 61-66.

[8] I. Spicka, M. Heger, J. Franz, The mathematical-physical models and the neural network exploitation for time prediction of cooling down low range specimen, Archives of Metallurgy and Materials 55/3 (2010) 921-926.