Contribution to the Assessment of the Data Acquisition Effectiveness in the Aspect of Gas Porosity Defects Prediction in Ductile Cast Iron Castings

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Abstract

The article presents an example of analysis of the influence of selected parameters deriving from data acquisition in foundries on the occurrence of Gas porosity defects (detected by Visual testing) in castings of ductile cast iron. The possibilities as well as related effectiveness of prediction of this kind of defects were assessed. The need to rationally limit the number of possible parameters affecting this kind of porosity was indicated. Authors also benefited from expert group's expertise in evaluating possible causes associated with the creation of the aforementioned defect. A ranking of these parameters was created and their impact on the occurrence of the defect was determined. The classic statistical tools were used. The possibility of unexpected links between parameters in case of uncritical use of these typical statistical tools was indicated. It was emphasized also that the acquisition realized in production conditions must be subject to a specific procedure ordering chronology and frequency of data measurements as well improving the casting quality control. Failure to meet these conditions will significantly affect the difficulties in implementing and correcting analysis results, from which INput/OUTput data is expected to be the basis for modelling for quality control.

Keywords: Foundry processes, Information technology, Gas porosity defects, Data acquisition

1. Introduction

Among the manufacturing techniques present in the mechanical industry, foundry technologies are one of the most complex technological processes. These are known processes in the field of metallurgy and alloy casting, involving high temperature, complex chemo and physicochemical phenomena.

Receiving the final product (cast), of the quality defined by its user, starts with the preparation of liquid alloy with the required metallurgical quality. In the next phase it is also important to produce the casting mould, the parameters of which will ensure achieving reproducible quality according to optimized technology.

The technological and organizational complexity of casting production results from the differentiation of the materials used in

castings production and the inevitable interrelations of the various stages, that is partial processes, which was stressed in [1,2]. It is significant that recipients of castings require fulfillment of ever more technically restrictive reception conditions. It is especially perceptible in the automotive industry (wall shading, gradient material). In foundry, along with using highly specialized apparatus and quality control procedures, it is necessary to complement increasingly sophisticated advanced ways of monitoring and production processes control [3]. This is related to the increasing number of casting process parameters subjected to monitoring, which can generate a very large amount of data. Extremely, this can lead to excessive redundancy of the collected data, and their large amount does not always correspond to process control needs. Therefore, one of the basic data acquisition tasks should be identifying the most important sources of information about casting partial processes and their assignment to particular groups of processes (including production of moulding sand and mould making, alloy melting, liquid melt pouring) in association with castings' quality [4]. It is necessary to group Input and Output parameters and assign them respectively as independent and dependent variables, depending on the accepted process control procedure.

The article assumes that the term "parameters" and the term "data" are used in a relationship: parameters in terms of quantitative or qualitative amount, and data - as a summary of assembled parameters making up the set being analyzed, allowing for its deliberate processing, e.g. using statistical tools, with continuous conclusions drawing and constant indication of controlling interactions in feedback (off-line, SPC methods).

The amount of recorded data in each group is never identical and results from different data acquisition procedures, and first of all, from differentiated chronology of collecting specific type of data as well as different frequency of making measurements, assigned to individual parameters. This causes that the combination of different groups of parameters on a single time axis is related to the temporal link between them, and in the best case with full identification referring to a particular case of filling up the mould and the final product obtained from this mould [5]. It happens that the case of a very large number of parameters quite often can lead to misinterpretation of the influence of some parameters on the Output value, for example the appearance of a specific cast defect. Authors believe that to avoid such situations, in the first place one should selecting the most significant parameters and their ranking, taking into account the criterion of the predicted influence on a given type of defect. This should of course involve recognized experts providing synergic linkage of theoretical knowledge about phenomena occurring in the cast-mould system with knowledge resulting from laboratory tests. This usually happens along a typical scenario of methodology of selective exposure of a given INput parameter (independent variable, measured directly) onto the OUTput property (dependent variable). In this particular case the authors consider as the Output feature the quality of the cast (e.g. specific type of defect).

As it turns out, reducing the data set size with the help of specialists can make the initial statistical analysis significantly easier [6,7]. It can also be assumed a priori that data acquisition may take place in a way that only parameters selected upon ranking are taken into account, hypothetically the ones most affecting the given type of defect. However, this may limit the

field of analysis in case other defects occur as well as in case their relation with other parameters, not appearing in the given ranking are being sought.

This paper presents a proposed methodology of identification of possible reasons influencing the occurrence of Gas porosity defects, detected by simplified non-destructive method – VT (Visual testing). It shows how important the way data is being acquired is in industrial conditions and indicates potential dangers.

2. Research conditions and methodology

Below there are presented conditions and the course of data analysis, obtained in cooperation with one of Western European foundries, which produces castings from gray and ductile cast iron, weighing up to 20 kg [8]. Castings are produced on an automatic moulding line with a horizontal division mould made of classic green sand. It is worth noting that no special scenarios were used for data acquisition, which are recommended for planning experiments in laboratory conditions or scheduled industrial tests. The database was based on the maximum obtained data quantity scenario, which involved an elaborate acquisition procedure. Initially, the procedure involved around 300 parameters relating to processes during production of all castings according to the foundry's customers' orders. The purpose of this acquisition was identification of compounds of parameters with the final casting quality without preliminary assumptions on what parameters will be used. The identification was to be both current and resulting from the need to better casting quality. An important original parallel goal of such a multiparameter acquisition is always an assessment of the stability of individual parameters [9].

The raw data collected for analysis were input in an appropriately developed EXCEL spreadsheet. Column headings contained parameter names, while rows contained values of these parameters ordered by previously assumed classification criteria (date, assortment, production series, etc.). Therefore, one particular row, herein referred to as the data record, corresponded to one series of filled moulds and by assumption contained an information set assigned to one assortment. It should be noted that the series may include several, a dozen or even dozens of casts of a given assortment.

The authors proposed to preliminary divide the database into two groups. The database labeled DB-01 contained only data derived from production processes (moulding sand parameters, metallurgical parameters, mould filling, etc.), while DB-02 - data referring to the cast product quality (defects, mechanical characteristics of samples cast separately, and/or adherent samples to casting and/or trepanned from casting). In the first approach DB-01 data was treated as data from the IN-put group, DB-02 - from the OUT-put parameter group.

An important condition was accepted of analyzing only complete data records, i.e. ones with all column filled in and not containing values being obvious errors for individual casting series or zero value (no parameter value). Moreover, three examples of assortments were taken into account, most often cast and casting technology were similar– e.g. type of cores and how they were embedded in the mould, the same cast iron grade). There could have been several such series during the day, so only.

mould). It should be noted that the measured moulding sand parameters can be divided into basic parameters (e.g. Moisture, Bentonite Active, Coal, Sand granulometry) and dependent on the basic ones - technological parameters of green sand resulting from

in this foundry weighting a dozen or so kilograms (their design a few records from a single day could have been acquired. A chosen limited fragment of the obtained and ordered database for the selected assortment is shown in figure 1

Fig. 1. Fragment of analysed database (MOULD – as DB-01 example and DEFECT CAUSE (kind) as DB-02 example). – described later in this text. Term "Internal …" means that defects are detected yet in the foundry.

After consulting the foundry (for the previously selected three assortments) the most frequently encountered defect of discontinuity in the form of Gas porosity was selected. Different causes of its formation were taken into account. The issue of this approach is discussed among others in [10, 11].

Subsequently, a ranking of the importance of production parameters' influence on the aforementioned defect was made, using consultations with experts from the technological universities with experience in cooperation with foundries. Finally, 12 parameters were selected including green sand parameters,2 parameters related with temperature of cast iron poured into mould: average value and its standard deviation. 1 parameter (OUTput Data) is Gas porosity (Table 1).

The temperature of the cast iron pouring into every mould was measured with a pyrometer and that was the only parameter which could be attributed to a particular cast (or castings from one the previous ones (such as permeability, compression, compaction, plasticity).

The average daily percentage of Gas porosity defects for all selected assortment casting series from a given day was referred to averaged parameter values from individual records, due to the impossibility of their individual association with this share. The collected data covered several months.

Table 1.
Selected parameters affecting the occurrence of defects of the Gas porosity type (obtained by the ranking of specialists)

INput Data	
GREEN SAND/ POURING PARAMETERS	
Green sand parameters	**Unit**
Moisture	%
Permeability	$m^2/Pa*s*10^{-8}$
Compression	g/cm^2
Compaction	%
Temperature	°C
Plasticity	%
Bentonite Active (final)	%
Bentonite Effective (entry)	%
Bentonite (added)	%
Coal	%
Shearing (x1000)	MPa
Cracking (x1000)	MPa
Pouring parameters	**Unit**
Pouring temperature (average)	°C
Pouring temperature (Standard deviation)	°C
OUTput Data	
QUALITY PARAMETERS - DEFECT	**Unit**
Gas porosity (quantity per series)	% per series

3. Analysis of potential relationships of selected parameters and predictability of Gas porosity defects

Relevant purpose of the article was to determine the relationship between parameters of moist bentonite moulding sand (green sand) and cast iron pouring temperature with the percentage share of Gas porosity defects in the current casting production. Earlier, during the first stage, the importance of individual influences of preselected parameters was examined with the use of regression analysis and ANOVA analysis. (below only the regression analysis will be presented) The parameters were previously selected and compiled in Table 1.

The results of the regression analysis showed unexpectedly low values of R^2 determination coefficient, ≤ 0.15. That means that the occurrence of Gas porosity defects in the casting is not in any relevant way associated with any of the parameters and forming a model facilitating predicting probability of this defect appearance is not strictly indicated. An illustrative example has been given in the chart below. It shows the results of a simultaneous study (important from the point of view of theoretical and practical knowledge) of influence of green sand permeability and the cast iron pouring temperature on gas porosity appearance. The method of point set approximation was applied with the method named Distance Weighted Least Squares, DWLS (see Fig. 2).
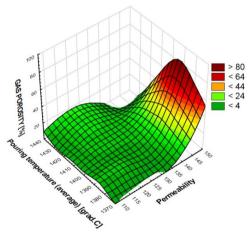

Fig. 2. The 3D graph (Statistica 13.0 programme) of variability of the percentage Gas porosity defect share detected in manufactured castings as a function of the green sand permeability parameter and average cast iron pouring temperature

Interpretation of the graph (Fig.2) does not confirm knowledge coming from the theory and practice of foundry. Also expectations as to the relation mainly of moisture, permeability and also other parameters (table 1) and pouring temperatures with the intensity of the appearance of Gas porosity defects in castings could not be confirmed. How should this be explained?

Each foundry has its own procedures according to which data acquisition is underway and it can also happen that apparatus, not subjected to periodic calibration, can cause systematic errors. This particularly applies to methods of control and identification of foundry defects based on visual testing when the foundry does not have a specialist laboratory of defect testing using other NDT (Non Destructive Testing) methods. In this type of identification (with the form of statements: yes or no, i.e. defect admissible / unacceptable) there is no information about the intensity of the defect, its location on the observed surfaces of castings subjected to visual inspection.

At the same time, it is worth noting relatively low standard deviations of selected parameters, which may indicate their satisfactory stability. The authors proposed carrying out an extended correlation analysis between 14 INput data variables. Correlation analysis was carried out in three ways (CorrSign): 1 - for all analyzed data records (CorrAll), 2 – separately for records, when defect "Gas porosity" (GP) occurs (CorrGP > 0) and 3 – when it does not occur (CorrGP = 0).

The result were several dozens of relations characterized with r-Pearson correlation factor. Table 2 shows selected results obtained only after putting together the two correlations methods (i.e. 2 and 3) and differences in correlation factors for the same pairs of variables. It was assumed that at least in one case (for CorrGP=0 or CorrGP>1) the value of the correlation factor is at least |0.5|. Difference values of r-Pearson factors for selected parameters pairs varied from 0.50 to 1.1. A hypothesis was formulated that the bigger Diff, the bigger significant influence of impact of given pair of parameters on gas porosity can be expected. This fact prompted more detailed analysis of the simultaneous influence of two (pair) selected in such a way parameters on the analyzed Gas porosity defect. For this purpose approximation of points' set was made by means of surface imaging (using DWLS method proposed in Statistica 13.0 programme).

Table 2.
Selected differences (only for Diff>=0,5) in correlation variable values r-P for the indicated pairs of variables

PX parameter	PY parameter	r-P CorrGP=0	r-P CorrGP>0	Corr Sign	Diff
Bentonite Active (final)	Plasticity	0,78	-0,23	0	1,01
Bentonite Effective (entry)	Plasticity	0,76	-0,12	0	0,88
Shearing	Bentonite (added)	0,82	0,17	0	0,65
Cracking	Compression	-0,06	0,58	1	0,64
Cracking	Bentonite Active (final)	0,85	0,27	0	0,56
Cracking	Bentonite Effective (entry)	0,84	0,30	0	0,54
Shearing	Plasticity	0,59	0,07	0	0,52
Bentonite Effective (entry)	Bent.Active(Bas)	0,96	0,45	0+1	0,51
Shearing	Bent.Active(Bas)	0,85	0,35	0+1	0,50

Description:
CorrSign – Correlation significance: 0 for CorrGP=0, 1 for CorrGP >0, 0+1 for CorrGP =0 and CorrGP >0
Diff – Difference Diff = ABS [r(CorrGP=0) - r(CorrGP>0)]

The most interesting dependence in terms of the correlation factor change was obtained for the first case (PX parameter – Bentonite Active (final) and PY – Plasticity where the r-Pearson factor value difference was slightly greater than 1 – see Table 2). Chart prepared in by the DWLS method is shown in Figure 3.

Maximum gas porosity values (100%) do not occur in practice. Surface shape on the graph shows only some trends obtained on the basis of approximation. This remark concerns also Fig. 4.

Figure 3 shows that with the increase in value of the Bentonite Active (final) and Plasticity parameters, probability of Gas porosity defect becomes smaller. Greater green sand plasticity values can be explained with a greater active bentonite content at the appropriate water content level in the green sand, but it is difficult to determine what physical mechanism of their influence on the formation of Gas porosity defect might be.
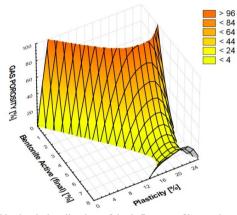

Fig. 3. Obtained visualization of the influence of bentonite active and green sand plasticity parameters on the variation of percentage of Gas porosity defect revealed in castings

As to the remaining pairs of variables (Table 2), not even hypothetical indication of their impact on the formation of Gas porosity defects was found. Unfortunately, among pairs influencing Gas porosity defect there were no parameters which could be considered to be the most important when ranking (including moisture, permeability, compression).
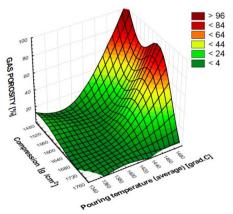

Fig. 4. Obtained visualization of the influence of the Compression and Pouring temperature parameter on the variation of percentage of Gas porosity defects revealed in castings

Figure 4 shows a rather surprising result for an example of the following parameter interaction: Pouring temperature (average) and Compression on Gas porosity. It is visible that the higher the pouring temperature and the lower the value of green sand Compression, the greater probability of Gas porosity defects occurrence.

Surface corrugation could indicate local tendencies, which are all the more difficult to explain the phenomenon of the influence of both parameters on the Gas porosity defect. Individual impact of pouring high temperature has not been confirmed. However, the answer to the question of the simultaneous negative impact of low durability casting mould, the answer is not unequivocal.

High casting temperature and low casting mould durability may significantly facilitate mould erosion. Penetration of cast iron into the structure of the moulding material often favors the intensity of the metal-mould reaction, which may also promote gas sources. Supposing in the initial phase of casting this gas penetrates into the top layer of the casting, and the Gas defect forming due to such action is identifiable (visual testing on the raw casting surface or after removal of machining allowance). Then however, the more likely disqualification defect would be sand inclusions / sand blow, penetration defect – it means - scabies or drop [12].

Further analysis of the selected data is being planned and to this end the procedure of data filtering by variables elimination from data sets according to different criteria and searching for the most probable model of important INput parameters influence on Gas porosity was developed. According to literature analysis, such actions are effective when at first there are no clear correlations of INput and OUTput parameters, as suggested by [13], among others. However, as results from specialist expertise, higher cast iron pouring temperature should in the first place affect the danger of Gas porosity defects occurrence. However, there is no possibility of a strict attribution of the known temperature of the cast iron jet at the entrance into the mould with the quality of a specific (single) casting and additionally the necessity of averaging makes the expected correlations not confirmed.

Reassuming, the methods presented in the article were preceded with sets ordering. They consisted of choosing one defect, the most often occurring in the foundry, for analysis. Then, with specialists' opinions, the parameters not influencing its emergence were eliminated. This has greatly reduced the amount of data. Another significant limitation was the choice of only three casting assortments for analysis. As it turns out, it is extremely difficult to identify relevant, direct or coupled parameters' effect on Gas porosity defect.

The article primarily points out the parameters, between which there is a large difference in correlation when Gas porosity occurs and does not occur. This indirect information has been used by the authors to study mutual relations of INput parameters synergistically affecting the appearance of defects. Only in one case can the results be probably optional (the higher the pouring temperature and the lower the green sand Compression, the greater the probability of Gas porosity defect occurrence). This fact encouraged the authors to look closer at modeling using the pouring temperature.

4. Summary

The article presents examples of analysis of parameters registered as part of a European cast iron foundry production. Measurements of these parameters were used to evaluate production stability conditions and the parameters suitability to control partial processes. Registering so many parameters often leads not only to expanding the collected databases, but also to data redundancy. The purpose was to use the

selected data to discover new knowledge in the form of soft models [8,14]. Authors on the basis of the available bibliography from the field of application of data exploration methods within machine engineering, confirmation of theoretical knowledge of soft modeling with its supporting experience from production in this industry was being sought.

It is worth noting that the aforementioned foundry has established a partnership with a specialized European scientific/implementation center, which provides services in the field of the use of widely understood statistical methods. The goal was the very search for identification of the correlation of many INput variables with Gas porosity defects. Mathematical formulas received by this center indicated quite clearly the existence of formal relations between Gas porosity defects and selected parameters derived from the acquisition [8, 15, 16]. Contrary to approach described in the article, this group did not limit the data amount (ranking of specialists). The usefulness of these formulas has turned out to be completely unsatisfactory, and the developed relations showed the existence of accidental interactions, which were to a large extent contradictory.

We, the authors have received the same extended databases from European foundry. We based their research on knowledge of physicochemical phenomena in the metal-mould system, supported by technological knowledge. It was known that synergistic influence of many parameters on the mechanisms responsible for the occurrence of Gas porosity defects is difficult to be estimated unequivocally. This is particularly important when dealing with big, unordered data sets.

It has once again been shown that data acquisition procedures, their planning, implementation, collection and development is a necessary condition for effective analysis and using its results to control and ensure quality in foundry. In further works, authors propose using their own method of exposing parameters based on the combination of the average pouring temperature and its standard deviation. This method will also take into account the frequency of percentage of defects occurrence.

In conclusion it should be emphasized that the search for relations between INput/OUTput data based on the acquisition in production conditions must be subject to a specific procedure ordering chronology and frequency of measurements as well improving the casting quality control as to defects identification and their quantification. Failure to meet these conditions will significantly affect the difficulties in implementing and correcting analysis results, from which INput/OUTput data is expected to be the basis for modeling for quality control.

Acknowledgements

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