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Preliminary communication

Improving the Surface Condition of the Casting of the Control Panel Cover

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Abstract: The purpose of the study was to develop a method for identifying and analyzing defects in aluminum castings. A correlation was made between visual examination, leakage, Ishikawa diagram, FMEA method, Pareto Lorenz diagram and the 5WHY method? in quality control. The sequential deployment of methods provides a multifaceted set of information. Integration of non-destructive testing (NDT) is found in the literature, but test results are not analyzed using quality management techniques. The integration of the indicated methods is an aspect of the model's novelty. A key issue in improvement activities is the identification of the cause of loss of quality stability. It demonstrates the need for models for diagnosing and analyzing nonconformities and the relevance of the subject matter undertaken. A test of the model in a foundry company was carried out, thanks to which the cause of the decrease in the level of quality was identified - in the studied period the percentage of nonconforming castings was 1.67% - 4.52%. The problem was the pouring of an alloy with the wrong temperature into the mold. The implication of the model made it possible to eliminate nonconformities.

Keywords: leak testing; mechanical engineering; quality engineering; quality management methods

1 INTRODUCTION

Castings are an essential part of any industry and therefore their quality is crucial, which should be by customer requirements [1]. Ensuring an adequate level of quality of castings is connected with the necessity of controlling a considerable number of factors influencing the process. However, the impediment is the inability to control all technological parameters at the same time. Therefore, a meticulous diagnosis of the casting indicating the correctness of its execution and the absence of inconsistencies is crucial [2-4]. Incompatibilities in aluminium castings are frequent problems causing a decrease in strength of the casting and an increase in the costs of the technological process, thus influencing further mechanical processing and operation of the casting [5-7]. As part of the diagnostic process in the foundry industry, one can notice a trend of implementing comprehensive testing methods, where castings are inspected using several non-destructive testing methods [8-11]. Quality control using visual [12] eddy current [13], penetrant [14], ultrasonic [15], radiographic [16] or leakage tests often performed after individual technological operations of the manufacturing process. Continuous progress in the use of automation in quality control, data processing and exchange, in line with the Industry 4,0 concept, makes it possible to achieve high precision measurements with more information to determine the condition of the product [17]. Performing an effective identification of inconsistencies in aluminum casting is one of the basic steps of the activities related to ensuring an appropriate level of quality of the casting process. Within the framework of maintaining process stability and repeatability of products, it is necessary to carry out quality analyses and then appropriate corrective and preventive actions. This indicates that not only the choice of process parameters and its supervision but also the choice of tools consistent with the concept of lean manufacturing is important. This activity will allow maintaining the appropriate level of quality and will enable rational management of resources, which will positively influence the financial aspect of the enterprise [18, 19]. One of them is the Ishikawa diagram based on cause-effect analysis of identified problems. The diagram is used to illustrate the cause-effect relationships, which helps to separate the causes from the effects of the analyzed situation and finally to see the complexity of the issue [20]. The FMEA (Failure Mode and Effect Analysis) method is also used to solve quality production problems. This method is based on the analytical determination of cause-effect relationships of potential product defects and the inclusion of the criticality (risk) factor in the analysis. When analyzing complex and multi-causal causal problems, it is advisable to use the Pareto-Lorenz diagram, which allows prioritizing the factors affecting the analyzed phenomenon. It assumes that in any system there are a small number of factors that have the greatest impact on the system as a whole, and the influence of the rest of the factors is less important. In the framework of further analysis of the identification of the causes of the decrease in the quality level of products, it is effective to use the 5WHY method, because the correct identification of the cause of the problem allows preventing the recurrence of the problem. The 5WHY method is based on a series of questions that allow you to see the source of the problem [21]. The quality management literature most often presents issues of quality analysis supported by the application of uniform quality management methods [22-26]. Despite the effectiveness of each of the quality management techniques, the application of them in the right sequence will increase the effectiveness of the research undertaken and achieve the synergistic effect which, in the analyzed industrial environment, will be the identification of the root cause of quality problems. However, there is still a lack of an integrally configured control-analytical model for effective diagnosis and analysis of the causes of manufacturing nonconformities. In addition, the lack of research indicating the integration of NDT diagnostics with quality management techniques to eliminate production problems has been pointed out which represents a research gap and points to the need to develop a model in which the tools used are arranged in an integrated sequence of activities. The study adopted the following scientific hypothesis: it is possible to accurately identify the cause of a major nonconformity in aluminum castings by skilfully integrating correctly selected quality management techniques. The purpose of the research was to develop a model integrally combining diagnostic activities (non-destructive testing - identification of nonconformities) with cause-and-effect analysis (quality management techniques) in solving quality problems. The model combines the use of visual method and leakage testing with subsequent quality management tools (Ishikawa diagram, FMEA, Pareto Lorenz diagram, 5WHY method) for inter-operational control and analysis. In addition, the research implemented a diagnostic model in a selected aluminum casting company. The scientific originality was the sequential use of quality management techniques in a specific production area. The developed model shows significant importance in the area of improvement. Thanks to the developed model, it is possible to continuously improve processes/products by subjecting it to successive analyses on the basis of which it will be possible to introduce new corrections and solutions leading to the effective elimination of the source of defects and providing new ideas to improve the properties of the product. The model can be used for highly complex processes in both mass and unit production.

2 MODEL OF DIAGNOSIS AND ANALYSIS OF CASTINGS QUALITY

To diagnose the quality condition of aluminum castings, it is possible to use the tests which do not have a destructive influence on the inspected product - non-destructive tests. However, it is advisable to use appropriate quality management tools as part of the quality analysis to remove identified defects. The developed model consists of a combination of appropriately selected NDT and quality management tools. In the model, the result obtained from one stage of the study is the input for subsequent activities. Diagram of the model of diagnosing and analyzing the causes of nonconformities in castings is shown in Fig. 1.

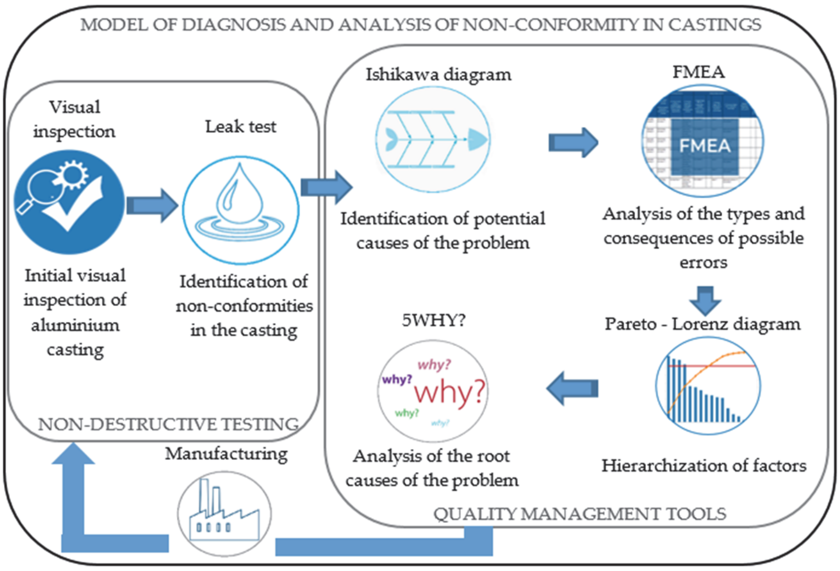

Figure 1 Schematic of the model for diagnosis and analysis of nonconformities in aluminum castings

The model for diagnosing and analyzing nonconformities shown in Fig. 1 allows us to go beyond passive control of inter-operational activities. Due to the speed of the test execution and their relative simplicity, visual tests in the model were situated as preliminary tests [14]. This type of research is considered to be economically viable. The main purpose of visual quality control is to quickly detect deviations from the expected state and also to isolate products classified as non-compliant. Visual testing makes it possible to detect the most dangerous discontinuities - narrow-gap discontinuities. Visual testing also allows the detection of imperfections in products, such as defects in shape, dimensional deviations, improper assembly, and the detection of surface discontinuities arising in the production process. However, this type of testing also has disadvantages which include: detection of surface defects only, difficulty of interpretation of observed discrepancies, the need for thorough preparation of the surface to be tested, and a strong influence of the environment on the test result. Identification of leaks is done by coating the (outer) surface of the casting with a surfactant (foaming) solution. The applied solution is characterized on one hand by high foaming properties and on the other hand by the possibility of free application of the solution on the tested area in such a way that during its application no foam is formed. Capillary leakage of an object at the boundary between two media causes air to penetrate, leading to the formation of air bubbles on the opposite side. In the test, the pressure difference on both sides of the casting walls should be high enough to reveal leakage in the form of bubbles forming. Checking for leaks relies heavily on meticulous visual inspection and looking for even the smallest indication of a leak. The test object shall be subjected to direct pressure. An Ishikawa diagram was used in the model to identify potential causes of nonconformities in the castings. This procedure is justified because at this stage of the analysis it is important to obtain a global overview of the different areas (method, machine, man, material, management, environment), since it is suspected that several possible causes are responsible for the problem. In addition, the use of a diagram allows you to show the relationship between the different parts of the problem [20]. The FMEA (failure modes and effects analysis) method was also used in the model. This method involves analytically determining the cause-and-effect relationships of potential product nonconformities and including the criticality (risk) factor in the analysis [24]. For complex and multi-causal problems, the model includes a Pareto-Lorenz diagram, which allows prioritizing the factors affecting the analyzed phenomenon. The diagram is built according to the assumption that in any system there are a small number of factors that have the greatest impact on the system as a whole, and the impact of the remaining factors is less important [26]. To be able to identify the root cause of a qualitative problem, it is recommended to use the 5WHY method, which prompts an analytical view of the problem [21]. The method not only allows you to focus on defining the root cause of each problem but also encourages employees to suggest ideas for process improvement. The developed model for diagnosing and analyzing the causes of nonconformities in castings uses a variety of methods and techniques to create more reliable synergistic systems for reducing nonconformities in castings.

3 MODEL VERIFICATION AND RESULTS

Verification of the developed model was carried out in one of the foundry enterprises characterized by a wide range of manufactured products for the automotive, medical, aerospace and food industries. The company is located in the southern part of Poland and has about 1,200 employees. The company manufactures aluminum products. The enterprise was chosen to verify the effectiveness of the developed model because after a design change in one of the cast products, the quality level of the production process became unstable - the product lost quality stability. The company has so far not used quality management techniques to improve products and ensure a stable quality level. The survey covered products of a certain type manufactured in the second quarter of 2021. This period was subject to detailed analysis due to an increase in complaints and a significant number of identified nonconforming products during inter-operational inspection (14% compared to the previous quarter). The largest number of nonconforming products was related to the casting of the control panel cover. This product was subjected to design changes which resulted in a qualitative divergence of the casting process. For this reason, the control panel shield casting was taken as the subject of the study. The scope of visual and leakage tests covered the surfaces of the entire casting, while metallographic tests focused on the areas where discontinuities in the material were detected. Experimental tests were carried out to evaluate the possibility of detecting discontinuities in the entire volume of the tested material. Nonconformity tests of the casting of control cabinet covers, contributing to the identification of leaks (especially the presence of oxides - the predominant type of nonconformity) were carried out after the casting process and the mechanical treatment of the product. Due to the significant volume of aluminium lids produced, detailed data on the number of nonconformities per month was used for the analysis (Fig. 2 to Fig. 4). Analyzing the graphs presented in Fig. 2, Fig. 3 and Fig. 4, one can notice a random character in the formation of the number of leaking covers, for example due to the presence of oxides passing through the walls of the casting. It was found that during the study period (July, August, September), the percentage of nonconforming castings of control panel covers ranged from 1,67% to 4,52%. The values achieved do not meet the requirements of the company standard specifying the maximum level of non-compliant products equal to the value of 3,0% of daily production. The data in Fig. 2 shows that in July the amount of nonconforming products is between 1,67% and 3,81%. On a monthly basis in July, the number of non-compliant products reached 2,66% and the number of leaks due to oxide inclusions was 1,86%. Analyzing the data from the month of August (Fig. 3), it can be seen that the number of leaking products is within the range of 1,90% - 4,29%. In monthly terms, the percentage of products in which the presence of oxide inclusions was identified amounted to 299 pieces (2,29% of all manufactured products). The obtained data concerning the number of nonconforming products and their types (Fig. 4) indicate that the range of nonconforming products has significantly increased in comparison with the previously analyzed months (2,14% - 4,52%). In this month the number of non-compliant cover castings amounted to 403, of which 292 pieces were products in which oxide inclusions were identified. Based on the leakage tests of the control panel cover castings, it was found that the leakage of the castings is mostly caused by oxide inclusions, which is illustrated in Fig. 2, Fig. 3 and Fig. 4.

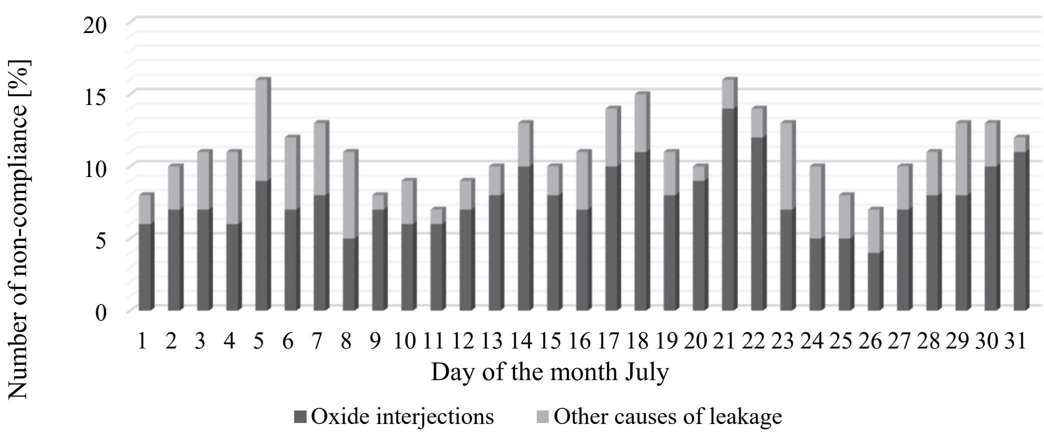

Figure 2 Total number of leaking control panel covers and their number caused by oxide inclusions only during the month of July

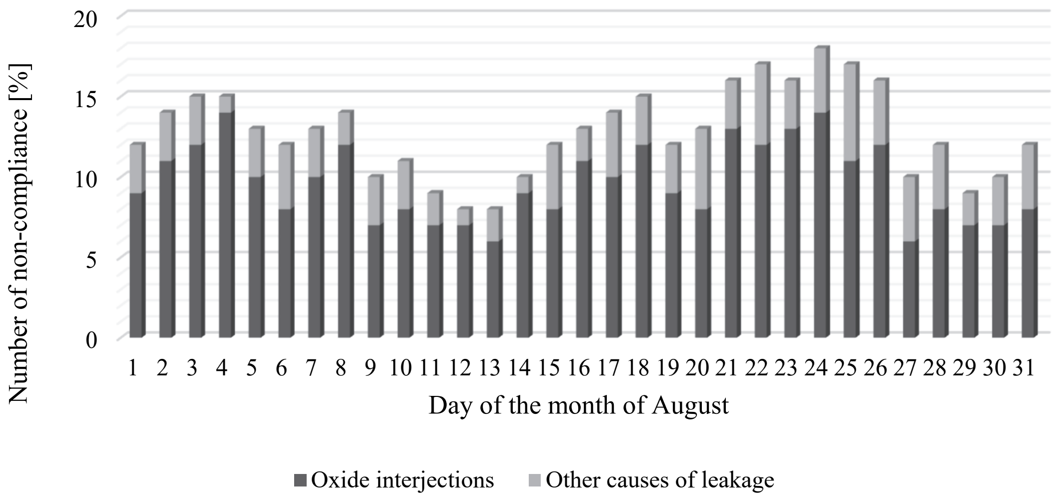

Figure 3 Total number of leaking control panel covers and their number caused by oxide inclusions only during the month of August

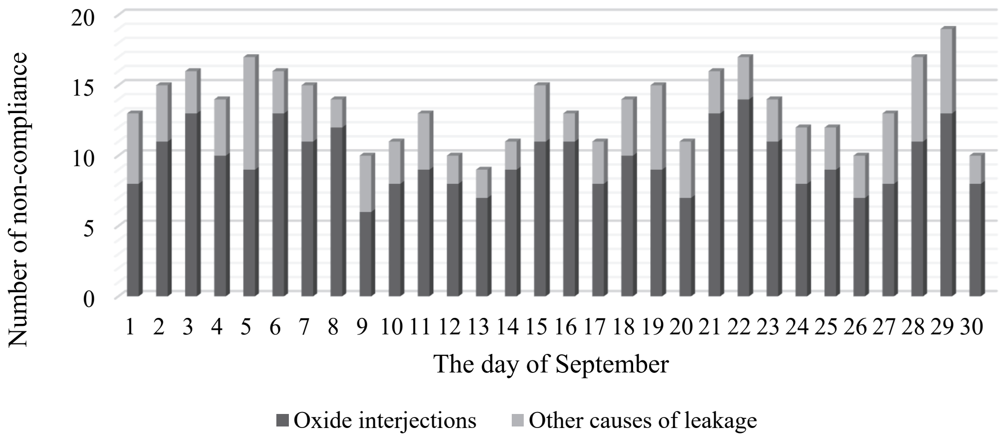

Figure 4 Total number of leaking control panel covers and their number caused by oxide inclusions only during the month of September

These figures also show the marginal contribution of other causes of cover leaks due to, inter alia, lumps, cracks, foreign material inclusions, the presence of pores or underfilling. Detecting leaks in industrial castings, including housing castings, requires specialized techniques and equipment. This precise diagnostic method makes it possible to identify where unwanted leaks are occurring, which is crucial to maintaining the structural and functional integrity of products. An example of a negative leakage test of a control panel casing casting is shown in Fig. 5. The helium casting leakage test stand was equipped with a suitable detector.

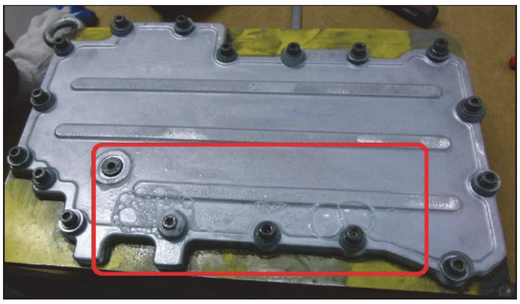

Figure 5 Leakage (discontinuity of material passing through, revealed in the water test by the penetration of water through the wall of the casting)

The workpiece, after being placed in a vacuum chamber, was filled with a mixture of nitrogen and helium. The device made it possible to very precisely determine the value of the casting's leakage. Typically, leaks occurred in the mold, holes, fissures and porous areas that allow liquid to penetrate.

Fig. 5 illustrates nonconformity in the form of a leak. For the purpose of visualizing the nonconformity, substances were used in the area of defects to get inside the object by pushing out air in the gaps forming bubbles. The discontinuity of the material passage for the purposes of visualization was identified in the water test by the penetration of water through the wall of the casting. Metallographic analysis of the areas where the leaks occurred revealed that most of the inconsistencies in the alloy structure were oxide inclusions. Fig. 6 shows an example of a microstructure in which an oxide was identified across the casting wall as the cause of leakage.

Primary oxide inclusions of die-cast aluminum alloys take the form of large inclusions with uneven distribution in the macrostructure. Such inclusions cause discontinuities in the alloy structure and reduce the atmosphere of the workpiece. They become a source of corrosion, significantly reduce the strength and ductility of the aluminum alloy, and often become a source of part fracture.

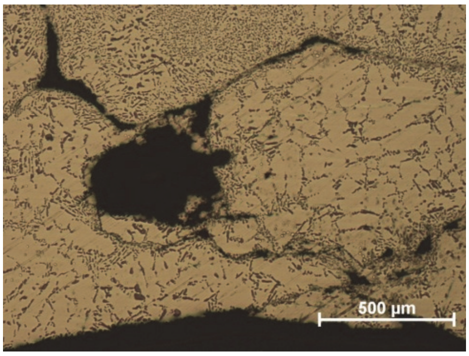

Figure 6 Oxide through the wall - the cause of leakage

In order to identify the cause of oxide inclusions in the casting, a sequence of methods such as Ishikawa diagram, FMEA, Pareto-Lorenz diagram and 5Why method was performed. Analyzing the problem using the indicated tools, a working group was formed consisting of the following employees: quality control manager, quality control employee, foundry manager and machining manager. Using brainstorming, an analysis of the reasons for the presence of oxides in the cover casting was conducted. An Ishikawa diagram (Fig. 7) identifies potential causes for the presence of oxides. The identified causes from the Ishikawa diagram (second-order causes) were analyzed using the FMEA method, with the aim of identifying cause-effect relationships determining the formation of potential nonconformities of the tested product, along with the risk factor. The FMEA analysis is shown in Tab. 1. In Tab. 1, the criteria LPW, LPZ, LPO stand for LPW (probability of nonconformity) - the number of occurrences of the defect; LPZ (importance of the defect to the customer) - the priority number of importance; LPO (potentiality of discovery of the defect by the manufacturer) - the priority number of discovery. The LPR indicator is the product of the LPW, LPZ and LPO sub-assessments.

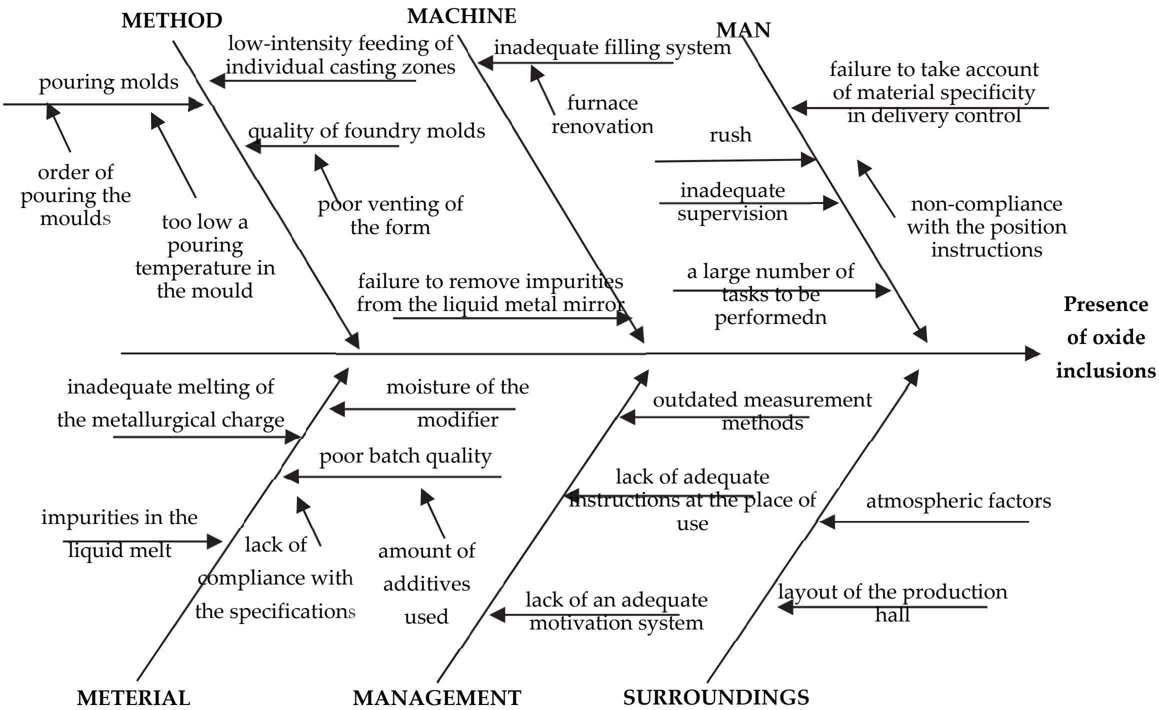

Figure 7 Ishikawa diagram of causes of oxide inclusions in control panel cover castings

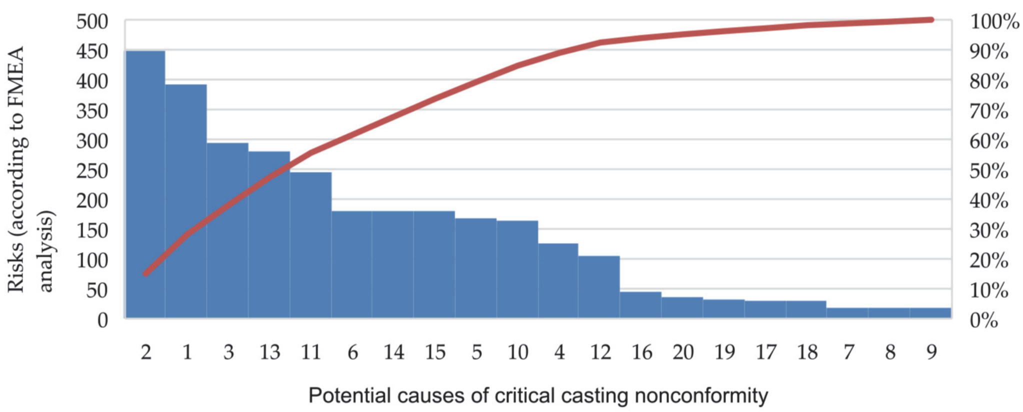

Figure 8 Diagram Pareto-Lorenza

Table 1 FMEA analysis of potential causes of oxide inclusions in control cabinet cover castings

No	Incompatibility	Effect	Causes	LPW	LPZ	LPO	LPR	Corrective actions
1.	Pouring molds (order of pouring the moulds)	Presence of fogging, oxide inclusions	Inadequately planned production process, lack of supervision, haste	7	8	7	392	Training for foundry employees, development of job instructions
2.	Pouring molds (too low a pouring temperaturę in the mould)	Presence of oxide inclusions, ripples	Inadequately planned production process, lack of supervision	8	8	7	448	Training for foundry employees, development of job instructions
3.	Low-intensity feeding of individual casting zones	Occurrence of defects in the form of underfilling, air bubbles		6	7	7	294	
4.	Quality of foundry molds (poor venting of the from)	Occurrence of defects in the form of underfilling, air bubbles		3	6	7	126	
5.	Failure to remove impurities from the liquid metal mirror	Occurrence of defects: inclusions	Inadequately planned production process, lack of supervision, lack of job instructions	6	7	4	168	Training for foundry employees
6.	Inadequate filling system (furnace renovation)	Occurrence of defects: underfilling, flooding	Inadequately planned production process, damage	6	7	5	180	Inspection, maintenance and repair of the furnace
7.	Rush	Employee mistakes	Overload of duties, poor organization of work	3	3	2	18	Analyze the responsibilities of staff positions, evenly distribute responsibilities among positions
8.	Inadequate supervisio	Lack of control and knowledge over employees' work	A multitude of responsibilities	3	3	2	18	
9.	A large numer of tasks to be performedn	Employee mistakes	Poor work organization	3	3	2	18	Reorganization of workplaces
10.	Failure to take account of material specificity in delivery control (non-compliance with the position instructions)	Low parameters of target castings	Inadequate supervision of suppliers, lack of control of liquid feedstock	6	7	4	164	Evaluating material suppliers, exercising control over process input material
11.	Inadequate melting of the metallurgical chargé	Low performance of target castings, occurrence of casting defects	Poor work organization, lack of supervision	7	7	5	245	Employee training, development of job instructions
12.	Impurities in the liquid melt	Low performance of target castings, inclusions in casting	Inadequate supervision of suppliers, lack of control of liquid feedstock	3	7	5	105	Checking the charge before pouring the mold
13.	Moisture of the modifier	Occurrence of defects: pores in castings, shrinkage defects	Inadequately planned production process, lack of control	8	7	5	280	Development of a control system and job instructions
14	Poor batch quality (lack of compliance with the specifications)	Low parameters of target castings	Inadequate supervision of suppliers, lack of control of liquid feedstock	6	7	5	180	Evaluating material suppliers, exercising control over process input material
15.	Poor batch quality (amount of additives used)			6	7	5	180	
16.	Outdated measurement methods	Low measurement accuracy, lack of compliance with imposed parameters	Low management efficiency	5	3	3	45	Implementation of up-to-date and adequate measurement methods
17.	Lack of adequate instructions at the place of use	Employee errors, haos	Low management efficiency, lack of supervision	5	2	3	30	Development of comprehensive job instructions
18.	Lack of an adeguate motivation system	Employee errors, tardiness	Low efficiency of personnel management	5	2	3	30	Creation of an incentive system
19.	Atmospheric factors	Dampness of charge, casting mold	Failure of heating or ventilation in the production hall	4	2	4	32	Inspection, repair, maintenance of heating and ventilation system
20.	Layout of the production hall	Obstruction of duties	Rapid expansion of manufacturing space	3	4	3	36	Reorganization of workplaces

In the next stage of the research, a Pareto-Lorenz diagram was made based on the results of the FMEA analysis (Fig. 8). The diagram made it possible to order the prioritization of factors (including second-order causes) affecting the analyzed quality problem. The numbering of potential causes of the quality problem in the Pareto - Lorenz diagram and the FMEA analysis are the same. Among the potential causes, improper pouring of the mold - too low pouring temperature - was considered the main cause. In addition, in order to determine the main cause of the deterioration of casting quality, the problem was analyzed using the 5Why method (Fig. 9). The analysis (Fig. 9) shows that the main reason for pouring the mold with an inappropriate temperature alloy was the failure to train a new employee, resulting from inadequate human resources management. The machine was operated by a newly hired employee who misread the work instructions. His insufficient experience and lack of training was a major cause of the nonconformity. During the analyzed period (July, August, September), the percentage of nonconforming castings of center covers ranged from 1.67% to 4.52%. On the other hand, the introduction of a method to search for the real causes of nonconformities contributed to an average reduction of 1.51% in this type of nonconformity (pouring the mold with an alloy of the wrong temperature caused by the lack of training of a new employee) and stabilization of the process. The model is a new and universal method that can be implied in any foundry company to ensure the stability of production processes. The universality of the model allows for its wider application, not limited only to the problem situations indicated in the study. The versatility of the model manifests itself in the possibility of its use in foundries in which it is important to ensure a certain quality of the manufactured aluminum products. The versatility of the model allows it to be used by both stable, procedurally solidified organizations and those that are just forming in response to market challenges.

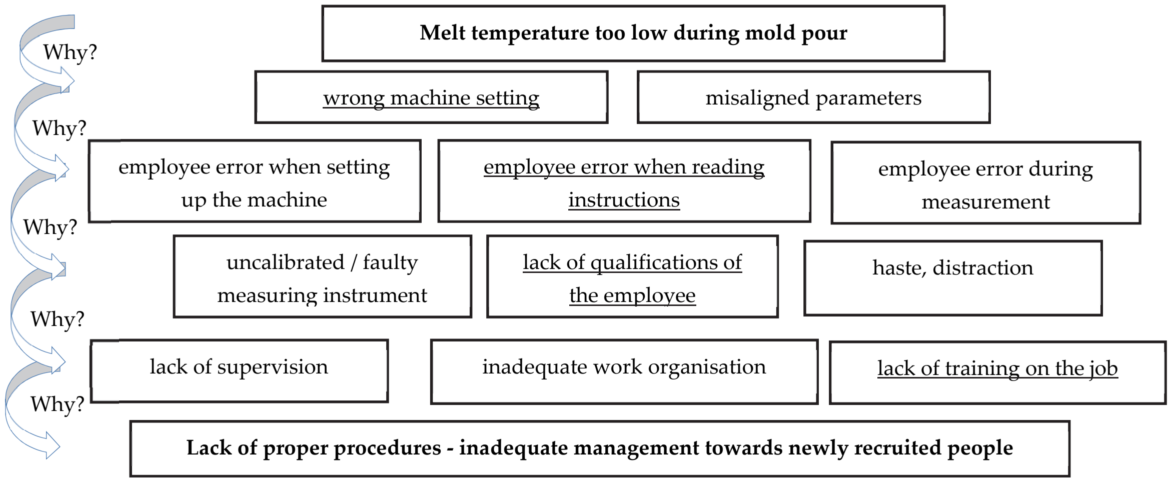

Figure 9 Run of the 5Why method for the melt temperature mismatch during pouring

4 DISCUSSION

Products manufactured by manufacturers must be properly adapted to the requirements of buyers, since quality is one of the key criteria for the success of manufacturing companies. In the manufacturing industry, cast products play an important role, with applications in every industry [27]. Therefore, it becomes important to ensure castings are free of non-conformities. However, this is often problematic due to the significant number of factors that affect castings during their production [28]. The literature points to the possibility of using non-destructive testing (NDT) to check the quality of castings. With NDT testing, it is possible to detect casting inconsistencies without significantly affecting its surface and structural properties [29, 30]. At the same time, it happens that the number of casting inconsistencies is large and it becomes troublesome to determine the root causes of their origin. For this purpose, the use of decision support tools (quality management techniques) is recommended [31, 32]. Scientific papers in the field of quality management often point to issues of quality analysis, which are supported by single quality management tools [22-26], or present proprietary models on issues of optimizing the course of production processes [33, 34]. However, there is an emerging gap from the scope of integrally configured quality control methods, which would allow the effective implementation of in-depth analysis of the causes of production nonconformities - the detection of the root cause of nonconformities. The developed model integrates a method belonging to the group of NDT methods and sequentially located quality management techniques leading to the identification of key causes of quality problems. It is possible to integrate the developed model with any number and type of detection methods. By recognizing the scope of quality problems, it is possible to improve and appropriately optimize the implementation of production processes and related control activities. The model was verified - an implication was made in one of the companies to identify and implement the analysis of nonconformities of control panel cover castings. In the analyzed case, the critical defects were nonconformities in the form of leaks, caused by too low pouring temperature of the mold by an untrained worker - which was identified by applying the appropriate sequence of quality management techniques. Identification of critical nonconformities and the root causes of the quality divergence of the production process with the use of appropriate quality management techniques enables the implementation of appropriate improvement and preventive production measures to reduce costs and production time.

5 CONCLUSION

Due to the increase in requirements for the service life of widely used working aluminum alloy castings, the issue of leaks in these castings is a very serious issue. The purpose of the research was to develop a model integrally combining diagnostic activities (non-destructive testing - identification of nonconformities) with cause-effect analysis (quality management techniques - identification of root cause) in solving quality problems. The scientific originality was the sequential use of quality management techniques in a specific production area. As part of the verification of the developed model, it was implemented in one of the foundries, which was carried out in the second quarter of 2021. The main conclusions in the context of solving the quality problem included:

- the leakage of the castings analyzed was mainly due to oxide inclusions,
- the share of other causes of lid leakage, such as gaps, cracks, foreign material inclusions, pores and underflows, was marginal.
- the key cause of the main nonconformities was the wrong way of pouring the mold (too low pouring temperature), which was caused by the lack of training of the new employee, resulting from inadequate management of human resources.
- the effectiveness of teamwork was indicated (a working group properly selected for the problem analyzed the quality problem using appropriate quality management techniques.

The solution of a quality problem using the developed model confirms the usefulness, versatility and correctness of the model's design. The scientific contribution is manifested in the popularization of the effective application of NDT testing and sequentially combined quality management techniques in specific manufacturing spaces. Limitations of the developed model are related to leak testing itself: lack of accurate indication of leaks, relatively long execution time of leak testing, and also relate to quality management techniques: the need for availability of historical data (quality data of the last few months). Future research directions will concern the expansion of the model - the creation of software on the basis of the presented model, which, implemented in the production space, will contribute to the automation of the implementation of analysis, including: rapid identification of critical nonconformities, detection of the degree of their impact on the decline in quality of a specific group of products, and identification of the root cause of critical nonconformities. The proposed software will be able to form components of methods supporting the processes of effective quality management.

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