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Risk Assessment of Defect Occurrences in Engine Piston Castings by FMEA Method

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Abstract

The FMEA (Failure Mode and Effects Analysis) method consists in analysis of failure modes and evaluation of their effects based on determination of cause-effect relationships for formation of possible product or process defects. Identified irregularities which occur during the production process of piston castings for internal combustion engines were ordered according to their failure rates, and using Pareto-Lorenz analysis, their per cent and cumulated shares were determined. The assessments of risk of defects occurrence and their causes were carried out in ten-point scale of integers, while taking three following criteria into account: significance of effects of the defect occurrence (LPZ), defect occurrence probability (LPW) and detectability of the defect found (LPO). A product of these quantities constituted the risk score index connected with a failure occurrence (a so-called “priority number,” LPR). Based on the observations of the piston casting process and on the knowledge of production supervisors, a set of corrective actions was developed and the FMEA was carried out again. It was shown that the proposed improvements reduce the risk of occurrence of process failures significantly, translating into a decrease in defects and irregularities during the production of piston castings for internal combustion engines.

Keywords: Casting defects, Casting quality management, Pareto-Lorenz method, FMEA process, Failure risk score

1. Introduction

The Failure Model Effect Analysis (FMEA) is a method consisting in analytical determination of cause-effect relationships for formation of product defects, while taking into account the criticality (risk) factor. It is aimed for identification of possible product (or process) defects, and their elimination or minimization of the risk connected with them [1÷4]. Thanks to this method, a process may be improved by subjecting it to successive analyses and, using the obtained results, introducing solutions which eliminate the sources of failures effectively and provide new ideas improving the product properties. The FMEA is carried out as early as during preliminary project study to obtain information on weaknesses and advantages of the product (process) so as to have an opportunity to introduce changes even

before commencing the production process. The FMEA requires working in a team of 4-8 persons led by a leader. This method enables to ensure the quality during the production process at the stages of planning and designing [5÷7]. Using the FMEA method, one should take the following actions in order as below:

- draft team members together with an FMEA team leader;
- select the object for the analysis of a process or its part;
- describe the current status of the product being manufactured;
- identify all defects, defining their causes;
- determine the significance of the defects, risks of their occurrence, and detectability;
- calculate priority number of the risk, LPR (from 1 to 1000);
- suggest corrective means and carry out the FMEA again.

2. Aim and scope of the studies

The goal of the paper is to define the cause-effect relationships for generation of defects during the production process of piston castings and calculation of risk level of the defect occurrence using the FMEA method. The scope of study includes:

- identification of most important defects during the piston casting and their categorisation by the Pareto-Lorenz method;
- determination of the LPZ; LPW and LPO numbers, and LPR;
- determination of corrective and preventive actions.

3. Methodology of the study

In the first stage of the study, the most important quality defects of the engine piston castings were identified [8]. Then, their per cent and cumulated shares were calculated, and they were categorised using Pareto-Lorenz analysis. The assessments of risk of defect occurrence were carried out in a ten-point scale (from 1 to 10) while taking three following criteria into account:

- significance of effects of the defect's occurrence (LPZ number),
- defect occurrence probability (LPW number),
- detectability of the defect found (LPO number).

Based on the product of these criteria, the priority number (LPR) was calculated, constituting the risk level for an occurrence of a given defect in the piston casting production process:

$$LPZ \times LPW \times LPO = LPR \quad (1)$$

As it results from the literature [1÷3], various categories of the meaning of the criteria mentioned above are used. Therefore, taking into account the specificity of the production process of engine parts used in the automotive industry, the individual components of these quantities were identified and were given their corresponding values in a ten-point scale. The results of the assumed criteria and their scale are shown in Tables 1-3.

Table 1.

Significance of effects of the defect occurrence criterion – LPZ		
LPZ	Significance of effects of the defect occurrence	
1,2	The defect does not affect the quality	Occurrence of defect is improbable
3	Very low	Low importance of the defect, low repair costs required
4	Low	
5	Transitory	The defect causes slight difficulties
6	Average	The defect affects the product quality moderately
7	Significant	The defect is significant. The product requires small corrections
8	High	The defect importance is high. The repair leads to a large cost
9	Very high	The defect impairs safety during use of the product
10	Product rejection	The product is rejected, corrective actions necessary

Table 2.

Defect's occurrence probability criterion – LPW number		
LPW	Defect occurrence probability	Number of defects
1	Occurrence of defect is improbable	<1 per 1,000,000
2		1 per 100,000
3	The defect occurs very rarely	1 per 50,000
4		1 per 10,000
5	The defect occurs sporadically, every now and then	1 per 5,000
6		1 per 1,000
7	The defect is repeated in some batches	1 per 600
8		1 per 400
9	The defect is repeated regularly	1 per 100
10		1 per 10

Table 3.

Detectability of the defect found criterion – LPO number		
LPO	Detectability of the defect found	
1-2	Very high	The control will detect the defect
3-4	High	The control means have a high chance to detect the defect
5-6	Average	The control will detect the defect probably
7-8	Low	It is probable that the control means will not detect the defect
9-10	Impossible	The control will not detect the defect

4. Results and their analysis

The most frequent defects of piston casting originating from the processes of casting and preparation of rings are shown in Table 4.

Table 4.

The most frequent defects of piston castings from the processes of casting and preparation of piston rings

Defect No.	Type of the most frequent defects	Percentage share	Cumulative share
1.	Hydrogen inclusions in the piston	20.25	20.25
2.	No adhesion on the ring	14.27	34.52
3.	Gaseous porosities in the piston	10.44	44.96
4.	Too high roughness of the ring	9.91	54.87
5.	Gas cavities in the ring	8.89	63.76
6.	Wrong chem. composition of piston	8.02	71.78
7.	Non-metallic inclusions in the piston	7.05	78.83
8.	Metallic inclusions in the ring	5.19	84.02
9.	Non-metallic inclusions in the ring	4.33	88.35
10.	Wrong chem. composition of ring	3.94	92.29
11.	Metallic inclusions in the piston	3.78	96.07
12.	Contraction cavity in the piston casting	1.17	97.24
13.	Piston cracks	0.71	97.95
14.	Misrun casting	0.65	98.6
15.	Lack of the ring in the piston	0.62	99.22
16.	Ring cracks	0.41	99.63
17.	Piston dimension default	0.27	99.90
18.	Piston shape defects	0.10	100.00

The data shown in Table 4 indicate that seven defects (hydrogen cavity, lack of adhesion of the ring, gaseous porosities in the piston, too high roughness of the ring, gas cavities in the ring, discrepancy of the chemical composition of the piston, and non-metallic inclusions) are responsible for 78.8% of all failures occurring in the production process of the engine piston castings. Eleven other defects cause 21.2% of found quality defects in the production process. Based on the data collected in Table 4, a Pareto histogram (relative number) and Lorenz curve (cumulative relative share) were plotted. A fragment of the plot corresponding to seven main defects is shown in Figure 1.

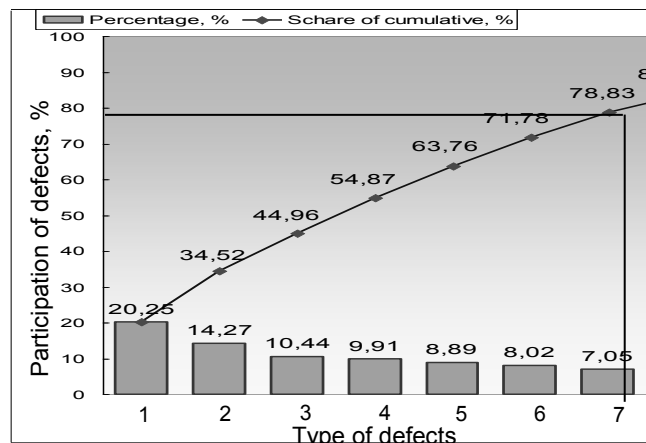


Fig. 1. A fragment of the Pareto-Lorenz plot for piston casting defects

The FMEA, in fact a PFMEA (Process Failure Mode and Effects Analysis) of the process of casting of motorcars engine pistons for seven main defects, is shown in Table 5.

Values of the LPZ; LPW; LPO numbers were assumed based on:

- internal quality procedures of one of the manufacturers of casting engine parts for the automotive industry;
- interviews with production supervisors of casting lines;
- significance of the defect and its results (for the manufacturer and for the customer);
- reports of irregularity complaints and repair costs.

Combined list of the criteria numbers for the significance of effects of the defect (LPZ), the defect occurrence probability (LPW), the detectability of the defect found (LPO), and their product (LPR) for the identified irregularities during the production process of piston castings for internal combustion engines is shown in Table 6.

For the explanation of the information provided in Table 5:

- the alphining process consists in immersing the ring in an Al alloy (called an alphining alloy) for several minutes (approx. 3÷4 min), in order to achieve a better connection of the ring with the piston in the result of diffusion processes between casting iron and Al-Si casting alloy;
- the process of refining of aluminium alloys consists in removal of suspended matter of non-metallic inclusions, including oxides, sulfides, nitrides, and in degassing of the liquid metal;
- the modification process consists in introduction of modifiers (Na, Sr) to the liquid alloy in order to refine the microstructure.

Table 5.

FMEA seven main defects of engine piston castings

Defect No.	Possible effects of the defect	Possible causes of the defect	Online control of the production process
1	- weakened piston-ring connection, - lack of adhesion of the ring	- low quality of the gas for refining, - carelessly executed refining process	- quality control of the refining gas, - control during every refining process
2	- drop of the ring from the piston, - seizure of the piston-	- touching piston rings with bare hands - dirt and moisture, - greasing of the ring	- workstation and process control, - control of the alphining alloy
3	- too poor properties of the piston, - limited operating time of the piston	- bad quality of crucibles, - no or poor melting loss removal	- control during every gas refining process, - workstation control
4	- bad alignment of the ring, - no connection with the piston, - seizure of the ring, - ring to be discarded-	- incorrect casting method, - the mechanical working carried out incorrectly, - negligent alphining process	- control of the process, - quality control of the metal moulds and the ladle, - control of the alphining process
5	- no connection with the piston, - low endurance of the ring, - microporosity of the ring	- incorrect casting iron method, - poor condition of the furnace brickwork - poor condition of the metal moulds	- control of the process of barrel casting, - quality control of the metal moulds and the ladle
6	- too low hardness and properties of the piston, - hindered heat treatment, - reduced time of failure-free operation	- low quality of batch materials, - no control of chemical composition, - improper modification process	- control of furnaces for melting of the alloys, - control of the alloy melting process, - control of chemical composition
7	- too poor properties of the piston, - excessive porosity and low endurance, - limited working life of the piston	- bad quality of crucibles, - the metal moulds not covered, - the refining process carried out incorrectly	- control during every gas refining process, - workstations control, - technological manuals control

Table 6.

Values of the criterion numbers LPZ, LPW, LPO and LPR

Name of the process	Defect No.	LPZ	LPW	LPO	LPR
Alloy refining	1	10	8	6	480
Alphining process of casting iron rings	2	10	6	6	360
Alloy refining	3	6	6	8	288
Ring casting and alphining process	4	8	6	6	288
Casting iron barrel	5	4	6	8	192
Al alloy casting	6	8	6	6	288
Casting and gaseous refining of the alloy	7	6	6	8	288

The last step of the FMEA consisted in an implementation of corrective actions in order to minimise circumstances of defect occurrence in the production process of the castings. These actions included, according to their classification into 3 categories:

- 1) in the scope of technological causes:
 - development of workstation manuals which will define the permitted and forbidden actions in detail,
 - modernization of casting equipment and alphinig stations which are most used up or their replacement with new ones;
- 2) in the scope of human-related causes:
 - instructing the workers on the significance of the individual technological operations and their effects for the quality of the production process,
 - improvement of professional qualifications and skills of the workers responsible for the most important technological operations (control of the chemical composition, casting);
- 3) in the scope of causes related with poor organisation of labour:
 - introduction of a more frequent control of the casting equipment quality (the furnace brickwork, the crucibles, the ladle, the condition of the metal moulds surfaces) and synchronisation of the permanent mould casting machine,
 - introduction of workstation control by production supervisors, and application of workstation monitoring where necessary.

After implementation of the corrective actions, the FMEA of the engine piston casting process was carried out again. A list of LPZ, LPW, LPO and LPR numbers after implementation of the corrective actions and differences between the LPR numbers “before” and “after” the corrective actions are shown in Table 7, and their graphical interpretation is shown in Figure 2.

Table 7.
Values of the criterion numbers after rationalizations

Defect No.	LPZ	LPW	LPO	LPR	LPR difference, %
1	10	4	6	240	50.0
2	10	3	4	120	66.6
3	6	3	8	108	62.5
4	8	4	4	128	55.5
5	4	4	8	128	33.3
6	8	3	6	144	50.0
7	6	3	8	144	50.0

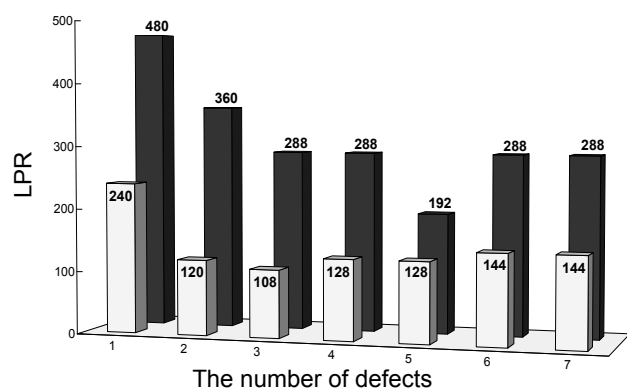


Fig. 2. The priority number LPR “before” and “after” implementation of the corrective actions (Tables 6 and 7)

5. Summary

The studies carried out indicate that seven defects (Table 4) are responsible for 79% of failures occurring in the engine piston casting process. The FMEA of the process carried out before implementation of the corrective actions proved that defect No. 1 (hydrogen cavities in the piston – LPR=480) is the defect having the highest priority number LPR. Detectability of this defect was defined as average, meaning that the control means used during the production process are not always able to detect the defect. Occurrence of this defect was defined as frequent, and its significance as very high and impairing safety of the production. Presence of this defect results in a product not meeting quality requirements. Occurrence of this defect causes a weakening of the piston-rings-cylinder connection, lack of adhesion of the ring, and in consequence it disqualifies the product as not being ready for shipment, and causes a very high loss. Another defect identified during the observation of the process was defect No. 2 (lack of adhesion of the piston ring – LPR=360). The third defect group with the highest LPR number value (288) are defect Nos. 3; 4; 6; 7. These defects result in, among others:

- low performance and low endurance of the piston,
- stoppage of mechanical working of the piston castings,
- stoppage of heat treatment of the piston castings,
- reduced working time of the piston-rings-cylinder system.

After implementation of recommended actions and a repeated FMEA of the piston casting process, it was found that the LPR number for the defects Nos. 2 and 3 decreased by approx. 60%. In the case of the defects Nos. 1, 4, 6, and 7, the corrective actions reduced the LPR number by approx. 50%, and for the defect No. 5, the risk level decreased by approx. 33%. It should be noted that the corrective actions being undertaken are quite general, and the results of these actions are individual matters of every enterprise accepting the level of the LPR indices.

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