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The use of Selected Lean Management Tools for Analyzing Defects in Pistons for Internal Combustion Engines

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Abstract

The article presents the most significant material defects found in pistons for internal combustion engines, along with a graphical method of categorization using a Pareto-Lorenz chart. For the top three defects (constituting approximately 80% of all issues), a slightly different Ishikawa chart was employed to identify the causes behind their occurrence. Remedial actions were proposed, to be implemented primarily within the interoperative quality control of piston casting. It was concluded that it is crucial to prevent the excessive iron content in the alloy used for alfin inserts (AS9 alloy), particularly for cast iron ring carriers. The research was conducted in collaboration with Federal-Mogul company in Gorzyce (F-MG), one of the largest piston foundries in Poland.

Keywords: Lean Management, Ishikawa diagram, Pareto-Lorenz chart, Casting defects, Engine pistons

1. Introduction

Coping with the rapid dynamics of the market environment and achieving a competitive advantage can be accomplished by adopting concepts like "Lean," introduced to the automotive industry by Taiichi Ohno in the 1950s. Referred to as Lean Production (LP) within the production domain, this method originated in Toyota's facilities, forming the foundation of the Toyota Production System (TPS) developed in the 1970s and 1980s. Lean Production (Lean Management) [1-4] is a production management approach driven by two primary objectives: minimizing all forms of waste (muda) and delivering the highest quality products to customers. These objectives can be achieved using numerous techniques (tools) such as 5S, Kaizen, Kanban, SMED, TPM, Poka-Yoke, which are geared towards enhancing production by visually addressing problems. Additionally, techniques that are simple, universal, and highly effective hold particular significance. These include, among others [5-9]:

- Pareto-Lorenz chart: it serves as a graphical representation of data on a decreasing bar chart. Additionally, the chart incorporates a Lorenz curve that connects the peaks of the histogram, indicating their cumulative values, and
- Ishikawa diagram: in cause-and-effect analysis, it is used to identify factors that might influence the quality of a process or product. It helps determine the primary causes requiring the most attention, allowing a holistic view of the problem by considering various aspects, both direct and "hidden." This approach enforces systematic thinking and considers the impact of multiple individuals and teams. When creating an

Ishikawa diagram, individuals from various departments (engineering, production, quality, R&D) with pertinent knowledge and insights are involved.

The beneficial impacts of "lean tools" are notably evident in industrial sectors particularly sensitive to dynamic market changes, where product quality and timely deliveries are pivotal for maintaining production continuity and satisfying customers. One of the examples where everything began is the automotive industry [10-15].

2. Objective and scope of the research

The primary goal of the research was to compile the most significant material defects in internal combustion engine pistons and, using an Ishikawa diagram, identify the factors primarily contributing to piston defects. The intermediate objective aimed to propose corrective actions.
The research was conducted in collaboration with Federal-Mogul company in Gorzyce, one of the foundries supplying pistons for various types of internal combustion engines. This company serves as a typical example of an OEM (Original Equipment Manufacturer), producing original parts (for both initial assembly and replacement) supplied to customers under their own brand.
To achieve the defined objectives, the following scope of research was adopted:

- characterization of the production process of pistons cast from Al-Si alloys,
- identification and prioritization of piston casting defects using the Pareto-Lorenz chart,
- cause-and-effect analysis of piston casting defects using the Ishikawa diagram,
- recommendation of corrective actions.

3. The process of manufacturing piston castings

The production of piston castings is a lengthy and intricate process. It can be divided into the following stages:

1. Melting of charge materials involves melting the charge materials (mixtures, pure elements, micro-additives, modifiers) to achieve the desired chemical composition of the piston alloy. Typically, it involves Al-Si with additives (Cu, Ni, Mg) with a near-eutectic composition (table 1). If the chemical composition meets customer requirements, the piston alloy is transferred to intermediate crucibles and transported to refining stations. (6-13%Si). If the chemical composition meets customer requirements, the piston alloy is poured into intermediate crucibles and transported to refining stations.
2. Alloy refining. Company employs a refining process using Cl-Ar mixture (under cover, due to the harmful effects of chlorine) followed by pure argon. After refining, the hydrogen content is measured, with an acceptable level of up to 0.1cm^3/100g of Al-Si alloy. The prepared piston alloy is then transported to the foundry station.
3. Alfin insertion in Al-Si alloy (AS9) - current pistons require the upper sealing ring to be embedded in a cast iron insert (table 2). This aims to lower temperatures and enhance the tribological resistance in the fire zone, prevent ring breakage, improve chamber sealing, and combustion efficiency during operation.
4. Piston casting - The pre-routed insert along with the salt core, reflecting the cooling channel, is placed into the mold cavity and filled with piston alloy. After cooling, the piston is removed by a robot, eliminating the gating elements, and transferred to the machining line.
5. Machining (turning, drilling holes, milling, etc.) to achieve the required dimensional accuracy of the pistons.
6. Surface treatment - (phosphating, graphitizing, cyaniding, anodizing, chroming) aimed at protecting the piston's side surface against corrosion, reducing friction between the piston and cylinder, improving oil wetting, filling micron irregularities on the piston's side surface, etc.
7. Quality control - interoperative and final (100% of pistons) using ultrasonic methods. It aims to identify the type and size of defects. F-MG's quality control department distinguishes two categories of piston defects: foundry-related and mechanical. Defects caused by human factors and improper management are omitted due to their low incidence.

Table 1
Chemical composition of the piston Al-Si alloy and AS9 alloy for alfining ring inserts, wt% (Al – rest) – average values

Si	Cu	Ni	Mg	Fe	Mn	Zn	Cr	Ti	Zr	other
Piston Al-Si alloy										
11,43	3,28	2,24	0,78	0,48	0,11	0,09	0,02	0,03	0,1	0,01
AS9 alloy										
9,5	0,2	0,05	0,03	0,35	0,1	0,05	-	0,05	-	-

Table 2
Chemical composition of the cast iron for ring inserts, wt% – average values

C	Si	Mn	Ni	Mg	Cr	P	S	Cu	Fe
11,43	3,28	2,24	0,78	0,48	0,11	0,09	0,02	0,03	rest

4. Materials defects in engine piston castings

The production process of castings for internal combustion engine pistons involves numerous variable parameters significantly impacting the final quality of the finished product. An analysis of the F-MG quality control department's results over 12 months revealed the most frequently occurring defects in piston castings (Fig.1):

- cracks between the insert and the cooling channel,
- damage during mechanical processing,
- incomplete fills (lack of material in the piston cast),
- lack of required adhesion between the ring insert and piston,
- shrinkage cavities, voids, and porosity between the insert and cooling channel,
- gas bubbles in the piston alloy,
- lack of concentricity between inserts, salt cores (representing cooling channels), and piston pin bores.

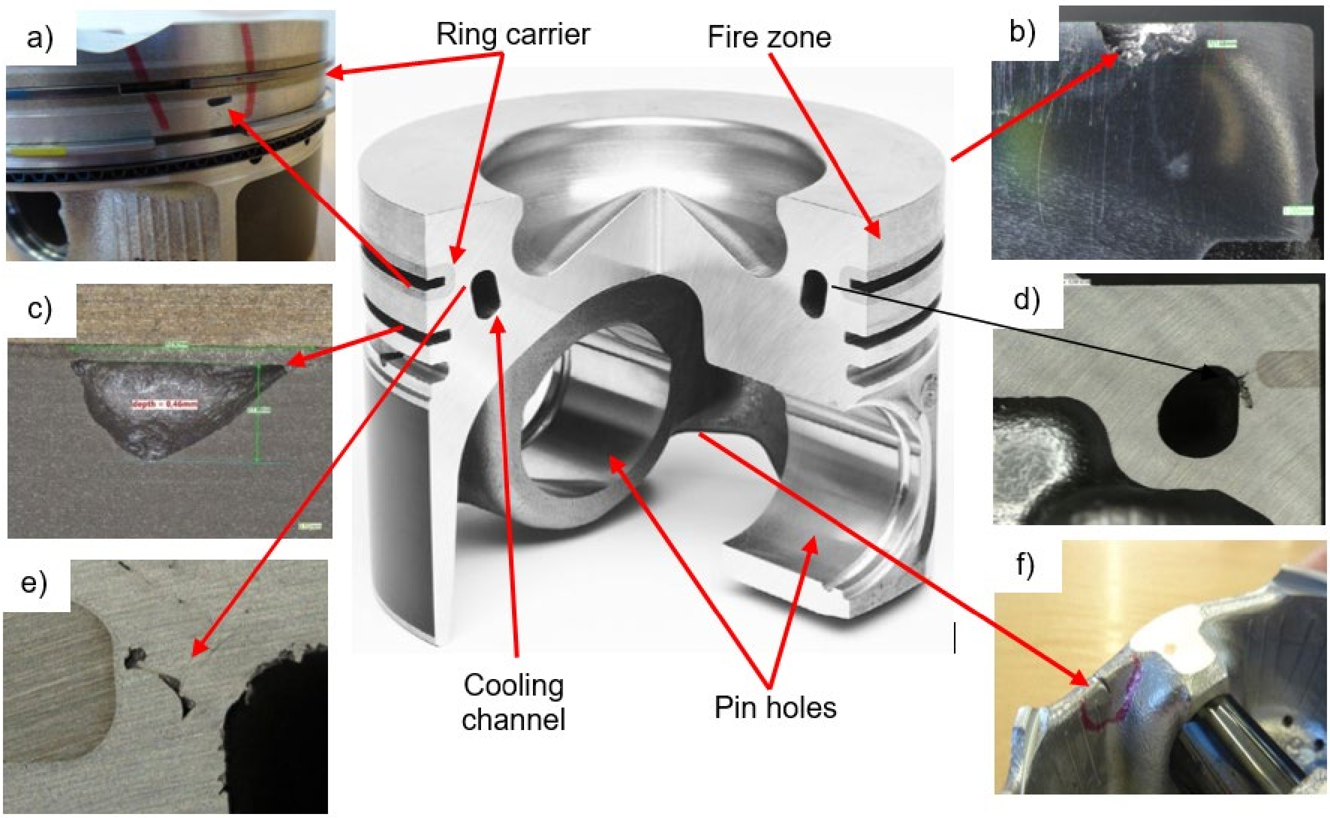

Fig. 1. External and internal view of the piston and the most common defects: a) hole under the ring insert; b) mechanical damage to the piston crown; c) void beneath the ring groove; d) void between the ring insert and cooling channel; e) porosity between the insert and cooling channel; f) crack in the piston pin area

5. Hierarchical arrangement of piston casting defects using the Pareto-Lorenz chart

The share of the most prevalent defects in piston castings using the Pareto-Lorenz chart is depicted in Figure 2. The research was conducted on a randomly selected population of 1000 piston pieces, with 500 for diesel engines and 500 for petrol engines, as the nature of defects in these pistons is similar.

The Pareto-Lorenz chart analysis reveals three primary defects in piston castings, constituting just about 70% of all defects, namely:

- defect No. 1: Cracks between the cast iron insert and the cooling channel, approximately 30% of all defects,
- defect No. 2: Exceeded share of unfavorable morphologically iron phases between the insert and the piston, approximately 20% of all defects,
- defect No. 3: Lack of adhesion of the insert to the piston due to excessive porosity, approximately 20% of all defects.

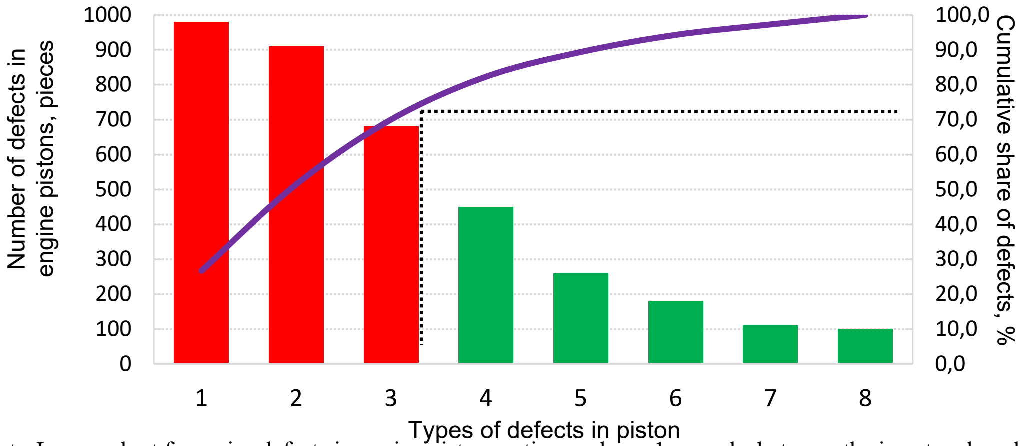

Fig. 2. Pareto-Lorenz chart for major defects in engine piston castings, where: 1 – cracks between the insert and cooling channel; 2 – excessive presence of unfavorable iron phases between the insert and piston; 3 – lack of adhesion of the insert to the piston due to excessive porosity; 4 – incomplete casting; 5 – voids under the piston ring insert; 6 – mechanical damage during piston machining; 7 – missing insert in the piston; 8 – excessive porosity of the piston alloy

6. The Cause-and-Effect Analysis of Piston Defects Using the Ishikawa Diagram

Before constructing the Ishikawa diagram, an interdisciplinary team was established to analyze the Pareto-Lorenz chart (Fig.2) depicting the primary defects found in Al-Si alloy pistons. To identify the causes of these defects, a brainstorming session was conducted. This approach was chosen because collectively developed suggestions regarding the causes of defects have a greater chance of successful implementation in industrial conditions.

For the cause-and-effect analysis, a slightly different Ishikawa diagram was employed. The difference lies in the atypical construction of the so-called "fishbone." Instead, the team adopted the 5M+E approach, which involves classifying the causes of discrepancies into main factors:

1. Machine - utilization of devices involved in the production process.
2. Method - manufacturing method of the product.
3. Material - utilization of all materials for product manufacturing.
4. Manpower - human involvement in tasks.
5. Management - production management methods.
6. Environment – environment al factors.

The Ishikawa diagram for defect 1 (cracks between the insert and the cooling channel) is depicted in Figure 3. Similar diagrams were created for the two subsequent defects (exceeding the proportion of unfavorable iron phases between the insert and the piston, and lack of adhesion between the insert and the piston due to excessive porosity). Each time, both primary and secondary causes were identified.

Regarding defect no. 2 (Fig.2), it was observed that the main causes of exceeding the proportion of unfavorable morphological iron phases between the insert and the piston mainly included:

- lack of control over the iron content in the AS9 alloy for the alfining process of ring inserts,
- absence of the use of so-called "morphological correctors" (e.g., Mn; Cr) for iron phase inclusions,
- lack of signaling methods (e.g., Poka-Yoke) for replacing the AS9 alloy when required,
- absence of protective covers preventing the iron insert from accidentally falling into the AS9 alloy,
- employees' lack of awareness regarding the adverse consequences of the iron insert dissolution in the AS9 alloy.

For defect number 3 (see Fig. 2), the primary causes of excessive porosity in the area where the insert connects to the piston are primarily:

- lack of inter-process refining of the AS9 alloy,
- absence of control over the content of gaseous impurities, e.g., hydrogen (hydrogen test), in the AS9 alloy,
- insufficient partial covers preventing the penetration of gaseous impurities into the AS9 alloy,
- employees' lack of awareness concerning the adverse effects of gaseous impurities in the AS9 alloy.

7. Corrective action

The visualization used to demonstrate the analysis results quickly illustrates what areas the team convened to solve the problem should focus on initially, determining the so-called "corrective actions". Among the main ones, we can include:
For defect number 1:

- more frequent inspection of the mold's thermal system and the positioning of the ladle during pouring,

- supervision of the refinement process of the piston alloy, monitoring refinement parameters,
- development of a motivation system for employees - Kaizen projects,
- courses and training sessions aimed at raising awareness among die-casting machine operators.

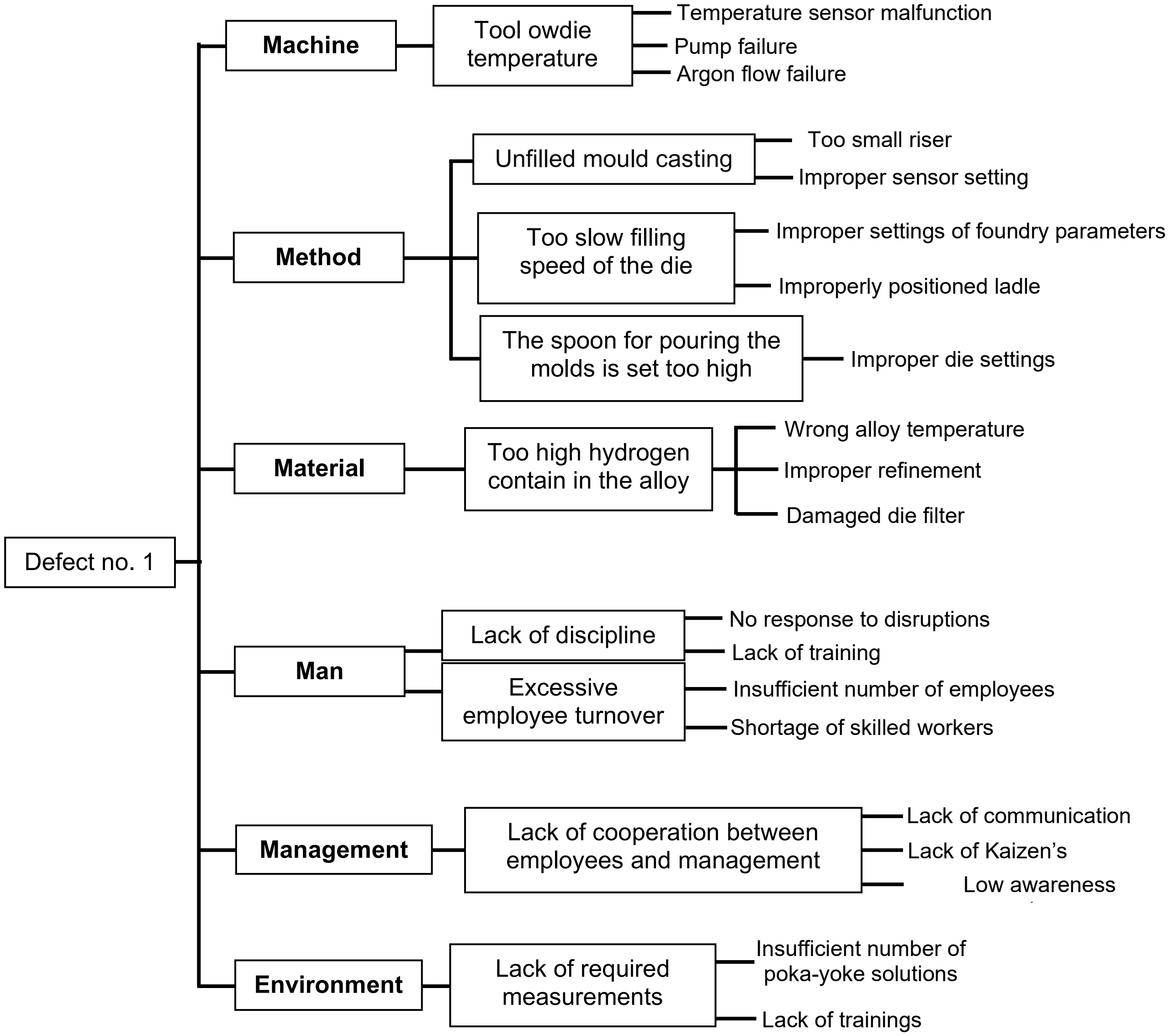

Fig. 3. Ishikawa Diagram for defect No. 1: Cracks between the cast iron insert and the cooling channel in the casting

For defect No. 2:

- implementing automatic monitoring of iron content in AS9 alloy during alfining,
- introducing Al-Mn or Al-Cr-based mixtures into the AS9 alloy raw materials,
- employing Poka-Yoke solutions to signal the replacement of AS9 alloy with new material,
- using mesh covers to prevent the cast iron insert from entering the AS9 alloy,
- implementing a procedure for accidental entry of the insert into the AS9 alloy,
- conducting courses and training to increase awareness among employees involved in alfining inserts.

For defect No. 3:

- introduction of control measures for gas impurity content, such as hydrogen, in the AS9 alloy,
- inter-process refinement of the AS9 alloy,
- introduction of shields to prevent gas impurities from entering the AS9 alloy,
- training sessions to increase awareness among employees regarding the impact of gas impurities in the AS9 alloy on the connection between the insert and the piston casting.

8. Summary

The application of universal, effective, and user-friendly Lean Management tools such as the Pareto-Lorenz chart and Ishikawa diagram is extremely useful not only during the production of piston casting. They also assist in problem analysis and preventing losses, determined by the limitation of defects already at the stage of technology design. At that point, the accuracy of actions taken is crucial for both the manufacturer and customer satisfaction. Corrective actions identified based on Pareto-Lorenz and Ishikawa diagrams should be assigned to specific leaders based on a detailed implementation schedule and established goals.

Based on the conducted research, it was concluded that during piston casting, special attention should be paid to controlling:

- critical process parameters, such as the temperature of the alloy, its contamination level primarily with iron and gas inclusions,
- the temperature and the blow system of the dies,
- the position sensors of the dies and casting ladles,
- the alfin process of iron inserts,
- the correct positioning of inserts and salt cores before pouring the piston alloy.

The research has also shown that proper training of operators handling casting stations is crucial for the piston casting process. High awareness, supported by instructions based on Training Within Industry (TWI) methods and motivational Kaizen systems used for supervising and instructing employees, significantly contribute to reducing defects. This improvement substantially enhances the quality of the process and the resulting product.

Furthermore, there should be a continued effort towards process improvement by collecting real-time production data concerning the level of defective products, their causes, and effective methods for reducing non-conformities and errors, for example, Poka-Yoke type solutions.

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