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Effect of Iron Phases Crystallization on the Durability of the Bimetallic Connection Between Ring Inserts and the Piston Casting

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Abstract

The article presents the most important causes of the unstable connection between cast iron ring inserts and the silumin casting of an engine piston. It is shown that manufacturing defects are mainly related to the alfin processing of inserts in Al-Si alloy (the so-called AS9 alloy). Exceeding the permissible iron content in AS9 alloy causes the crystallization of brittle β-Al_5FeSi phases. Their unfavorable morphology and large size are the main reasons for the weakening of the diffusion connection between the inserts and the piston, causing an unacceptable proportion of defective products. The study presented in this work was conducted under industrial conditions on a population of 10.000 pistons. Quality control data, production parameters, as well as the micro- and macro-structures of the cast iron inserts, and the interface area between the inserts and the silumin piston, were analyzed. Material and technological solutions have been proposed to reduce the occurrence of casting defects at the insert-piston joint. This includes the introduction of so-called "morphological correctors" of the β-Al_5FeSi phases, reducing the possibility of gaseous impurities in the AS9 alloy and optimizing the temperature of the alfin alloy.

Keywords: Crystallization, Al-Si alloys, Iron phases, Piston casting, Automotive industry

1. Introduction

The automotive industry is characterized by, high-quality requirements, a high degree of standardization, and, in most cases, production in large batches. Metal objects for automobiles are manufactured in one of three ways: casting, forming, or hybrid processes [1]. Casting is still one of the cheapest and most efficient ways to produce automotive components, including those that work in demanding conditions. An example is the pistons of internal combustion engines, which are now mostly cast from aluminum-silicon alloys (so-called silumin). At the top of such a piston the "ring zone" is located, which contains from 1 to 4 rings in two-stroke engines and from 2 to 4 - in four-stroke engines. Their number depends mainly on the compression ratio and engine design. The function of these rings is to seal the combustion chamber and scrape excess oil from the cylinder wall. For this reason, they are often made of ductile or malleable cast iron [2,3]. To strengthen the working area of the rings and obtain effective dissipation of heat from the top of the piston, they are embedded in a cast-iron insert ("ring carrier"), in which a groove is cut for the actual ring. To create a durable connection between the cast iron and the piston alloy, the inserts are subjected to the so-called "alfin processing". This procedure involves briefly immersing the insert in an Al-Si alloy - Table 1 (known as AS9) to form a diffusion layer [4-6]. Once cooled, the inserts are assembled in the die-casting machine and poured with piston alloy. In the past, piston designs with inserts were used only for heavily loaded diesel engines, operating at combustion pressures of 2.5 to 3.5 MPa, and for gasoline engines at 1.0 to 1.5 MPa. Today, inserts are used in all types of engine pistons for both gasoline and Diesel, including small and large-capacity engines [7].

2. Research problem

Statistics of final quality control obtained from the industrial partner of this research Federal-Mogul Gorzyce sp. z o.o. company shows that, in addition to improper machining of pistons, the most important group of causes of rejections of products are casting defects (about 8% of all defects). Considering that this particular company produces about 26 million pistons per year, and the average defect rate is about 3%, the number of scrapped pistons due to casting defects is about 62.4 thousand per year. These quality problems are detected only at the end of the production process during the final control of the pistons, which generates additional losses.

The study conducted [8] showed, the main casting defect appeared to be related to the presence of iron phases (especially β-Al_5FeSi phases) within the immersion and diffusion layers arising during alfin processing. Due to the brittleness and unfavorable morphology of these phases, they cause weakening of the insert-piston interface, contributing to an increased proportion of defective products. Iron phases are formed when the permissible iron content of the AS9 alloy is exceeded. Thus, iron content in alfin alloy is a critical criterion for ensuring functionality and correct operation of the piston-ring-cylinder system. However, it is still necessary to clarify the relationship between the alfin processing parameters and the stability of the manufacturing process as well as the quality of the final products.

Eliminating (or reducing) the crystallization of β-Al_5FeSi, phases, i.e. not allowing the iron content in the AS9 alloy to exceed the limit, leads to lower costs. It should be noted that due to the nature of the production cycle and the need for appropriate production buffers between the insert alfin stations and the final quality control, the feedback time for exceeding the iron content of the AS9 alloy can be long. This means that an operator, unaware of the problems, can produce inserts/pistons that do not meet quality standards for many cycles. Detection of defective insert-piston connections at the time of their formation allows for cutting costs in further manufacturing processes. This is achieved by reducing the load on equipment, energy, and the consumption of materials in subsequent production stages (machining and surface treatment) which are unnecessary in the case of products that do not meet quality requirements.

Based on the above information it seems reasonable to analyze in detail the causes of the formation of an unstable connection between the piston and the ring insert, as well as to propose a solution to this problem through corrective and preventive steps.

3. Research methodology

3.1. Purpose and scope of the study

The purpose of the research was to analyze the key parameters of quality control of the alfin processing, and on this basis to detail the causes of emerging casting defects at the insert-piston interface. The identification of the sources of these defects will result in tangible economic benefits in the form of reduced production costs.

The production of pistons for a 1400 cm^3 gasoline engine (the largest share of orders) was selected to evaluate the course of the alfin processing of inserts. The research was conducted on an isolated inserts alfin processing line at Federal-Mogul Gorzyce, on a population of 10.000 pistons. The scope of the research included:

- determining the share of casting defects appearing at the interface between the iron inserts and the silumin piston,
- analyzing inserts alfin processing,
- identifying potential reasons for the lack of adhesion between the insert and piston,
- proposing directions for potential problem solutions.

3.2. Test site

The analyzed alfin process was carried out on a semi-automatic alfin station, which is shown in Figure 1.

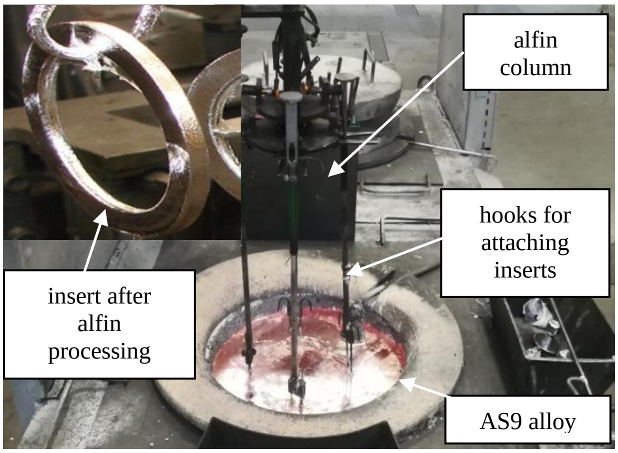

Fig. 1. Industrial stand for ring inserts alfin processing

The object of the study was casting defects occurring at the junction between the cast iron insert and the gasoline piston cast from AlSi11Cu4Ni3Mg alloy, shown in Figure 2. This figure also demonstrates the correct microstructure of the piston-insert joint, with the immersion and diffusion layer visible.

Identification of casting defects at the interface of the ring insert-piston junction and the adhesion measurements of the insert to the piston surface were carried out using the US Harrandt line and ultrasonic-penetration methods at the Federal-Mogul Gorzyce facility.

In addition to the tests conducted following the industrial partner's quality control standards, a detailed analysis of production data was performed. The parameters of the materials used in production (cast iron alloy for inserts, AS9 alloy) as well as the alfin processing itself were analyzed. Obtained data were then confronted with the results of microscopic tests conducted on the optical microscope MeF-2 Reichert coupled with an EDS Voyager Noran X-ray spectrometer.

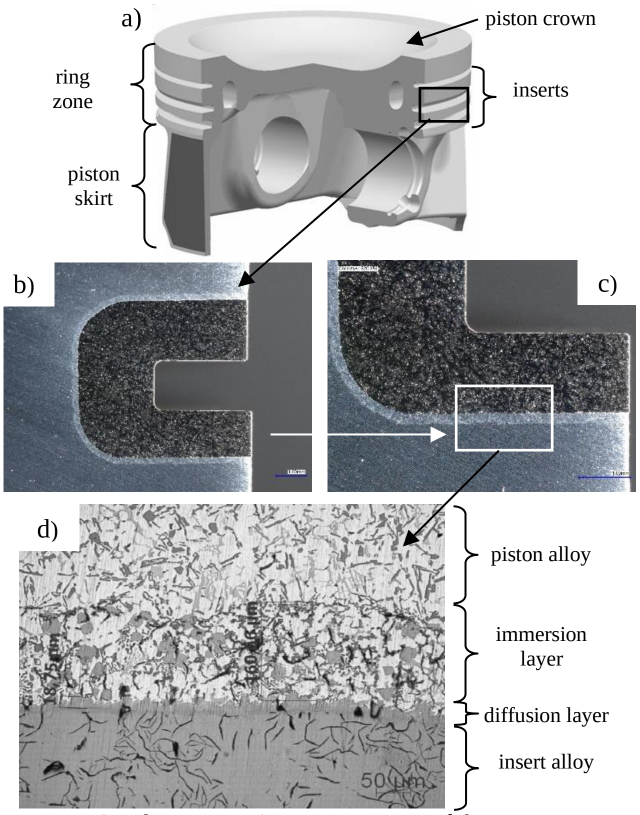

Fig. 2. Gasoline piston a); macrostructure of the insert-piston contact area b, c); microstructure of the insert-piston junction d)

4. Results

4.1. Quality control tests

In the first stage of the study, based on statistical data from the Quality Control Department of Federal-Mogul Gorzyce, a classification of the main causes of improper connection (so-called "breakage") of the insert to the piston body was made, as shown in Figure 3.

According to company guidelines (Federal-Mogul industry-standard TS1E-010-020, Tenneco Nurnberg GmbH, Germany), a diffusion joint between a cast iron ring insert and a silumin piston body around its circumference is considered to be of inadequate quality if at least one of the following conditions is met:

- rupture of the top (T) surface of the insert - more than 7%,
- rupture of the bottom (B) surface of the insert - more than 7%,
- overlap (O) of defects - more than 3%.

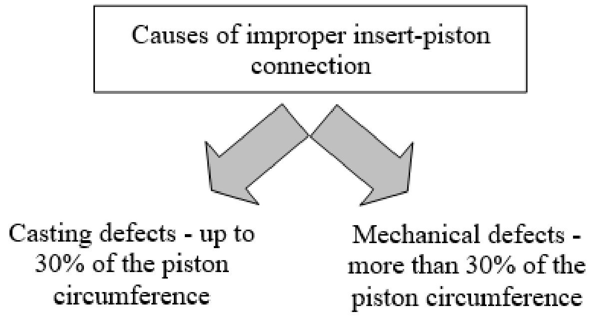

Fig. 3. Classification of the causes of the improper connection between the cast iron ring insert and the piston body.

Quality control tests of the insert-piston connection are carried out on 100% of the products. The pistons are tested by ultrasonic heads on the entire insert circumference during piston rotation around its axis. The pistons are oriented upside down (with the crown facing down). Adhesion is tested on the top (T) and bottom (B) surfaces of the insert - Figure 4.

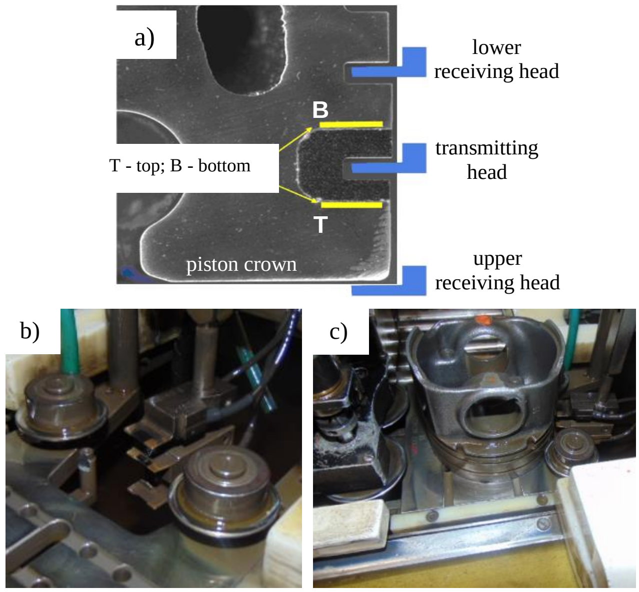

Fig. 4. Method of measuring connections between the insert and the piston: arrangement of measuring heads a); measuring stations b, c)

When a defect is detected, the Harrandt line indicates the location of the defect (top or bottom surface of the insert), its percentage, and the type of defect (casting or mechanical), as exemplified in Figure 5.

Figure 5a shows that the defect occurs in the top surface of the insert at about 10.39% of the piston circumference. Thus, it is a casting-type defect (up to 30% of the piston circumference - Fig. 3). Considering that the tested piston has a nominal diameter of Ø69 mm, (circumference of 217 mm) so the defect occupies about 22.5 mm of the piston circumference (Fig. 5b).

In the same way, the identification of all defects at the interface between the insert and the piston (in the study population) was carried out, finding that 24 pistons (out of every 10 000 units) have a qualitatively incorrect diffusion joint between the iron ring insert and the Al-Si alloy piston.

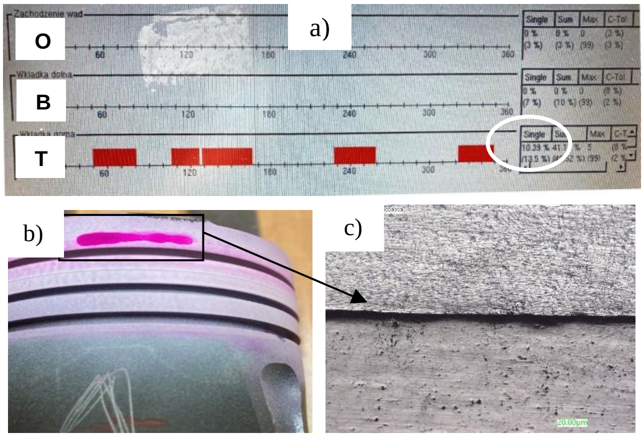

Fig. 5. An example of a casting defect at the insert-piston interface: screenshot from Harrandt systems a); location of the defect b); microstructure within the localized defect c)

4.2. Production data analysis and microscopic examination

To determine the potential causes of this unfavorable phenomenon, in accordance with the adopted methodology and the purpose of the study, the parameters of AS9 alloy (Table 1), austenitic Ni-Resist cast iron for the production of ring inserts (Table 2), and the alfin processing (Table 3) were analyzed.

Table 1.
Parameters of AS9 alloy for alfin processing

Chemical composition of AS9 alloy according to TS1E-012-008/2 (Federal-Mogul industry standard, Tenneco Nurnberg GmbH, Germany), wt% (Al - rest)							
Si	Mg	Cu	Mn	Fe	Ni	Zn	other
8.5 to 10.00	up to 0.03	up to 0.20	up to 0.12	up to 0.35	up to 0.05	up to 0.05	up to 0.02
The overheating temperature in the melting furnace: 800ºC ± 10ºC							
AS9 alloy temperature in the preheating furnace: 780ºC ± 10ºC							
Ar flow rate in the ladle: 12 l/min. ± 1 l/min							
Cl flow rate in ladle: 0.6 kg/h ± 0.4 kg/h.							
Refining time of the ladle (1000 l capacity): 10 min. ± 30 s							
The concentration of gases in the alloy (in the ladle): max 0.15cm^3 /100g alloy							

Based on the test results obtained and analysis of statistical data from the Quality Control Department of Federal-Mogul Gorzyce it was concluded that the most important parameters of AS9 alloy for the alfin processing of inserts are:

- exceeding the content of more than 0.35 wt%. Fe (Fig. 6),
- exceeding nickel content of more than 0.05 wt%,
- the introduction of gases into the AS9 alloy which mainly causes the formation of hydrides and oxides (Fig. 7).

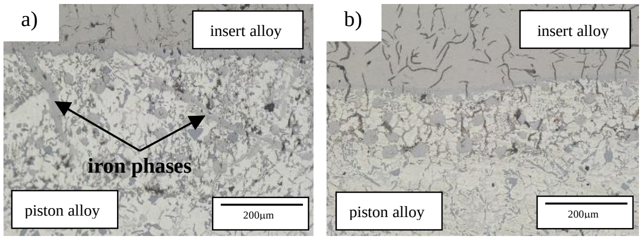

Fig. 6. Microstructure of the insert-piston joint: above 0.35 wt% Fe a); up to 0.35 wt% Fe b)

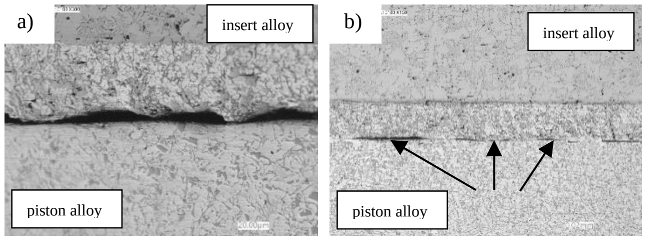

Fig. 7. Microstructure of the improper liner-piston connection: no immersion layer a); so-called oxide "film" (arrows) b)

An increase in the iron content of the alloy and the associated formation of iron β phases can both weaken the bimetallic connection as well as cause a complete lack of contact between the insert and the piston casting. The mechanism for this second phenomenon can be twofold. Long, more than about 500 µm β-Al_5FeSi lamellar phase precipitates can limit metal flow (feeding) and lead to shrinkage porosity [8] (Fig 8). Secondly, on the iron precipitates, oxide layers are deposited restricting the filling by the piston alloy of the area around the insert which leads to the formation of misrun-like defects.

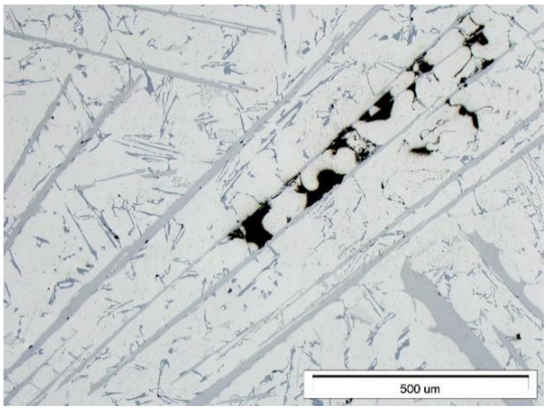

Fig. 8. Long (more than about 500 µm) β-Al_5FeSi phase precipitates along with visible shrinkage porosity

On the other hand, the presence of oxides in the alfin alloy may contribute to the heterogeneous nucleation of iron-rich intermetallics. These oxides act as substrates for the nucleation of primary phases. The authors [9-11] particularly indicate the so-called oxide bifilms in aluminum alloys as potential nucleation sites. Their outer surfaces may exhibit a favorable energy state for the formation of iron phases.

Analysis of the data presented in Table 2 allows to conclude that the most parameters of cast iron for the production of ring inserts are:

- nonconforming chemical composition and nonconforming (according to ISO 945-1:2008) microstructure in terms of the size and form of graphite precipitates (Fig. 9),
- maintaining the required degree of roughness of the insert after blasting (Fig. 10).

Table 2.
Parameters of cast iron for the production of inserts.

Chemical composition of cast iron type Ni-Resist EN-GJLA-XNiCuCr15-6-2 according to TS1E-012-006 (DIN EN 13835:2012), wt% (Fe - rest)							
C	Si	Mn	Ni	Cr	Cu	P	S
2.4 to 2.8	1.8 to 2.4	1.0 to 1.4	14 to 17.0	1.0 to 1.6	6.5 to 7.0	up to 0.08	up to 0.1
Hardness: 140 HB±20 HB							
Blasting time: 6 min. ± 1min.							
Surface roughness of the insert after blasting Rz = 20 μm ± 0.5 μm.							
Shelf life after blasting: max. 24 hrs.							
Insert heating: 230ºC ± 10ºC; 2.5 hours ± 30 min.							
Shelf life after annealing: max. 24 hrs.							

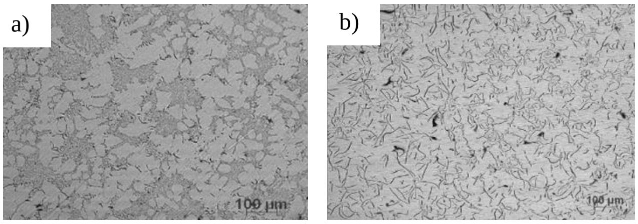

Fig. 9. Microstructure of EN-GJLA-XNiCuCr15-6-2 cast iron: not consistent with the standard a); consistent with ISO 945-1:2008 b)

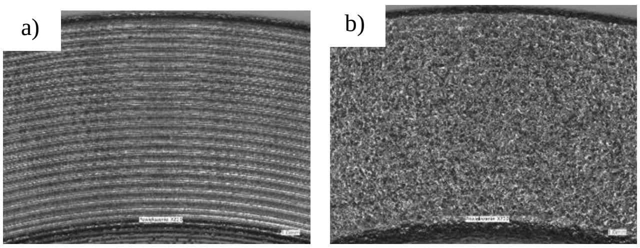

Fig. 10. Macrostructure of the cast iron ring insert: before shot blasting with visible traces of machining a); after shot blasting b)

It should be mentioned here that the inserts are produced by a separate technological process - centrifugal casting. The resulting casting has a form of a long tube which is then cut to the size of individual inserts. The inserts are then subjected to shot blasting to remove traces of machining (Fig. 10a). However, to ensure adequate contact with the alfin alloy, it is necessary to achieve the right surface roughness during this process (Fig. 10b).

Analysis of parameters summarized in Table 3, as well as the alfining process itself, it was possible to indicate the most important factors affecting the quality of the insert-piston connection:

- the temperature of the AS9 alloy in the preheating furnace,
- meeting the thickness of the immersion and diffusion layers,
- meeting the alfin processing time,
- ensuring adequate cleanliness of the surface of the insert (Fig. 11),
- continuous control of the increase in iron content in the AS9 alloy,
- eliminating the possibility of the insert falling into the AS9 alloy,
- ensuring adequate process control and repeatability.

Table 3.
Parameters of the alfin processing of inserts.

Alfin processing time: 330 s ± 15s
Alfin processing temperature: 780ºC ± 10ºC
The time between the removal of the insert from the AS9 alloy and pouring of the die: max. 45s
Use of alfin column vibration to remove gas bubbles from the surface of the insert
The thickness of the immersion layer: from 70 to 300 μm.
Diffusion layer thickness: from 5 to 40 μm.
Morphology of the immersion layer: no iron phase precipitates of the β type.

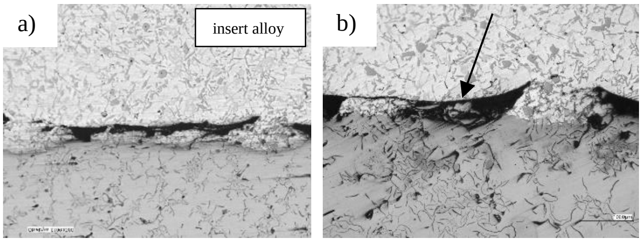

Fig. 11. Microstructure of improper insert-piston connection a), visible dirt and inclusions (arrow) on the surface of the insert b)

Analyses of the alfin processing carried out under industrial conditions made it possible to determine the causes of the increase in iron content in the AS9 alloy. In addition to the insert immersion process itself, the increase in iron content is influenced by the steel tooling used and human factors. The latter involves inserts accidentally falling into the alfin bath. In the event of such an incident, the inserts cannot be removed from the furnace, so they gradually increase the Fe content. It should also be noted that the main factor affecting the rate of iron diffusion during alfin processing is the temperature of the AS9 alloy and process duration [12].

5. Conclusions and outlook

The share of casting defects on the contact surface between the iron ring inserts and the silumin piston casting indicates that the problem of proper connection between these components is important from both a process and economic point of view. Production data analysis shows that the main causes of the defects are material, technological (process), and human factor problems occurring during the alfin processing of ring inserts. As the process proceeds, the iron content of the AS9 alloy increases (iron atoms diffuse into the alloy), reaching a limiting value that makes it necessary to replace the alloy. The used alloy defined as AS9+Fe is treated as scrap and sold at a lower price compared to the input material. Considering the continuity of production and its scale, it is estimated that the project partner Federal-Mogul Gorzyce company consumes about 100 Mg of AS9 alloy per month, which confirms the validity of the research undertaken in this regard.

Based on production data and performed analyses, it was found, that from the material point of view, the main reason for the casting defects occurring is that the iron content in the AS9 alloy exceeds 0.35 wt%. For the Fe content around 0.35 wt%, no casting defects related to the insert-piston interface were observed.

On the other hand, from the point of view of alfin processing technology, it is necessary to:

- pay special attention to reducing the possibility of gaseous impurities in the AS9 alloy, causing porosity at the interface between the insert and the piston,
- carry out research on optimizing the temperature of AS9 alloy in the preheating furnace towards lowering its value.

5.1. Directions of material changes

According to studies [4,6,8,13], intermetallic phases of the type $Al_XFe_YSi_Z$ with different stoichiometric proportions are mainly responsible for the durability of the connection between the insert and the piston. Their morphology results from crystallization conditions and iron content. Most of these phases, in the poured state, solidify in a lamellar form (visible under the microscope as needles), with sharp edges, causing the propagation of microcracks and stress concentration, resulting in the impermanence of the diffusion layer. In slow-cooled Al-Si alloys (about 1 $^oC/s$), with a content of more than 0.4 wt% Fe, undesirable, among other things, are precipitates of brittle β-Al_5FeSi phase, which, due to low coherence with the matrix and large size - increase the brittleness of the alloy.

Observation of microstructures of AS9 alloy, especially with more than 0.4 wt% Fe content indicates that long β-Fe phases precipitates contain central or edge cracks, mainly longitudinal and/or transverse. These cracks are often accompanied by shrinkage porosity of up to 70%, which further reduces the ductile properties of AS9 alloy.

Literature data [14-16] indicate that a good way to reduce the negative influence of iron phases in Al-Si alloys are methods involving the introduction into the liquid alloy of "correctors" that change the morphology of the β-Fe phases. The predominant ones are mainly high-melting elements (Mn, Mo, Cr, and Co), which in combination with iron form phases with more "rounded" edges, spherical shapes, and smaller sizes. An example of such high-melting-point phases, are: $Al_{12}CrMn$ (in Al-Si-Cr alloys) and Al_6FeMn or $Al_{15}(Fe,Mn)_3Si_2$ (in Al-Si-Fe-Mn alloys).

Thus, further research should be carried out in the direction of selecting the most effective alloying additive, determining the content in relation to iron, and developing the technology for its introduction into the AS9 alloy under industrial conditions. Studies in this area are already underway.

5.2. Directions for process improvements

Another method to reduce casting defects at the insert-piston interface is a well-designed technological process and its control plan. Key in this regard is, in particular, limiting the entry of gaseous impurities (oxides, hydrides) into the AS9 alloy, causing porosity within the diffusion and immersion layers. An analysis of production conditions at Federal-Mogul Gorzyce allowed the following solutions to be proposed:

- the use of furnace covers during the alfin processing of inserts to reduce the penetration of gaseous inclusions into AS9 alloy,
- the so-called "intermediate" refining, which should be carried out during the alfin processing,
- optimizing the temperature of the AS9 alloy in the preheating furnace.

It is interesting, especially from the economic point of view, to lower the temperature of the AS9 alloy (slowing down the diffusion of iron), thereby "extending" the increase in iron content and the service life of the AS9 alloy. Preliminary studies indicate that lowering the temperature of the AS9 alloy is possible and results in achieving the desired goal without increasing the proportion of casting defects. Research in this area is currently being conducted.

Acknowledgments

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