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Casting of Combustion Engine Pistons Before and Now on the Example of FM Gorzyce

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Abstract

The article discusses the most important changes in the construction of permanent mould casting machines, as well as the method of casting engine pistons and their construction on the example of Federal-Mogul (FM) Gorzyce. The system of automatic cooling of the presently used permanent mould casting machines coupled with robots which pour the liquid alloy ensures uniform crystallization of the pistons and optimal efficiency of the casting process. As a result of the necessity to improve the engine efficiency and thus reduce the fuel consumption and harmful substance emission, the construction of the pistons has changed as well. The piston castings, which are produced by gravity casting for metal moulds, have undergone a diametric transformation. Typical piston designs for gasoline and Diesel engines are shown together with the most important parts of the piston, the crown (combustion chamber) and the guide part (skirt). Depending on the type of engine, the present pistons characterize in differently shaped crown, a slimmed internal construction as well as component participation (cooling channels and ring inserts), and the piston skirts undergo surface treatment procedures.

Keywords: Casting, Silumins, Pistons, Permanent moulding casting machines, Surface treatment

1. Introduction

The requirements set for combustion engine pistons have been systematically rising in the recent years. This mainly refers to increased thermo-mechanical loads as well as low combustion gas emission and fuel consumption. The need for a reduced car mass and high rotational engine speed have caused an increase of the mean and maximal working chamber pressures and inertial forces. These expectations can be fulfilled through e.g. different solutions realized inside the engine. These include increasing values of temperature and pressure in the cylinders, which set the highest requirements for the heart of the combustion engine, i.e. the piston.

After World War II, in Rzeszów, Wytwórnia Sprzętu Komunikacyjnego (WSK) (Transport Equipment Production Plant) was created, which produced casts from aluminium, magnesium and copper alloys for the automotive and aircraft industry. In the 1970s, WSK produced rims from Al-Si-Mg alloys and starting from 1980s, at the plant in Gorzyce, pins, ring inserts and pistons were produced. In 2001, WSK Gorzyce was acquired by Federal-Mogul Powertrain, and it is presently owned by Tenneco (FMG). Initially, the casting of liquid metal took place in metal moulds by means of the gravitation method in a vertical system. Single permanent moulds were mounted on the casting machines and the mould filling was performed manually with the use of special casting ladles (Fig.1). The metal crystallized in the permanent mould equipped with simple systems of cooling the



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most important components: the main core and the pin cores, which enforced directional solidification of the cast towards the riser head located in its upper section. The then used alloy for gasoline and Diesel engine pistons was mainly silumin AlSi12 [1-6].

The permanent moulds of the old type consisted mainly of: the main core and the pin cores, die cast blocks and top core.

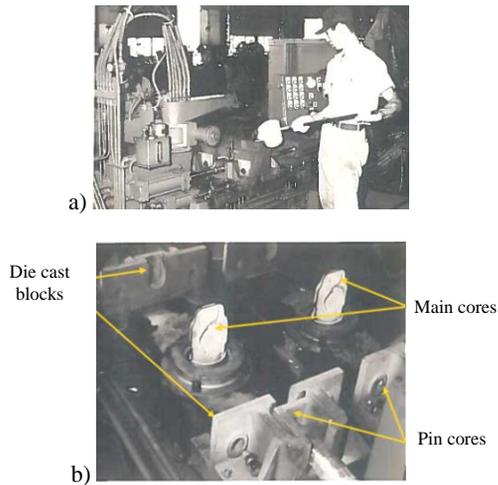


Fig. 1. Old method of casting pistons:

a) manual casting; b) single permanent mould casting machine [7]

At the turn of the 1980s and 1990s, the permanent mould casting machines for piston casting were slightly modernized, however, they were still single-chamber machines (Fig.2). They had the function of cooling only the main core, which caused different rates of piston crystallization.

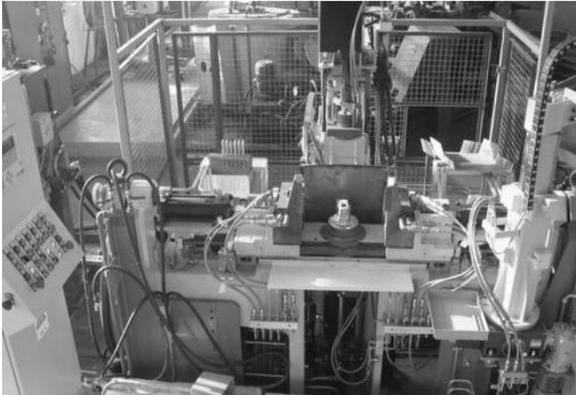


Fig. 2. Permanent mould casting machine for casting single pistons [8]

The engine pistons from the 1970s and 1980s were quite massive and not equipped with additional components submerged in the cast. After the mechanical treatment, their skirts were not covered with any protective layers. An exemplary cast of a gasoline combustion engine and Diesel engine piston of the “old” design has been shown in Figures 3 and 4.

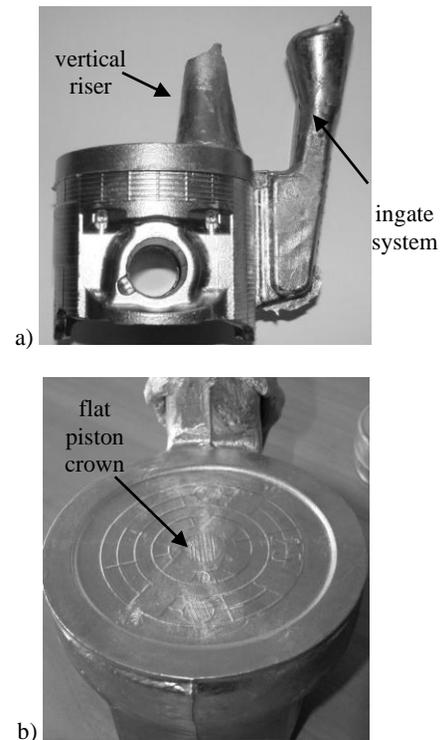


Fig. 3. Casts of an previous gasoline engine piston with diameter $\text{\O} 90$ mm; a) after lowering the permanent mould casting machine; b) simply flat piston crown [7]

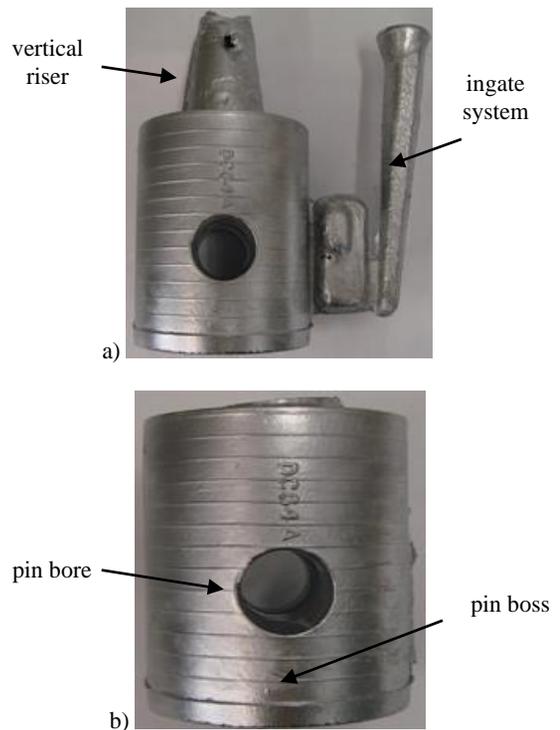


Fig. 4. Cast of an old Diesel engine piston with a) diameter $\text{\O} 110$ mm; b) piston casting after cutting off ingate system and riser [7]

After the cutting off of the ingate system elements, the semi-product underwent heat treatment and mechanical treatment, where it acquired the final shape and dimensions.

2. Aim and scope of studies

The aim of the studies was to point to the main changes in the construction of permanent mould casting machines and silumin casts of combustion engine pistons in the period of 50 years of production at Federal-Mogul Gorzyce. For the realization of the assumed aim, the scope of studies included:

- description of the changes in the construction of casting machines and permanent moulds for the casting of silumin engine pistons,
- modernization of the systems of cooling the main permanent mould elements,
- changes in the construction of pistons for Diesel and gasoline engines.

3. Development of casting machines

At present, the fully automatized casting stations are adapted to continuous casting of pistons. The dosing of a strictly determined amount of the liquid alloy, the placing of the piston components in the permanent mould casting machine (e.g. ring inserts and salt cores) and the unloading of the casts are performed by casting robots (Fig.5). The permanent mould casting machines are supplied with a power hydraulics system, which automatically opens and closes the particular elements of the permanent mould. Owing to the complex cooling systems (Fig.6), the time of piston cast crystallization has been unified and the process efficiency has been improved. The permanent mould casting machines have been equipped with double permanent moulds (for each side), owing to which it is possible to simultaneously produce a double number of casts (Fig. 6).

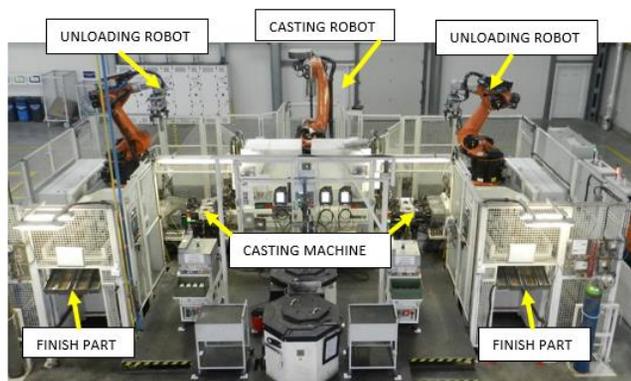


Fig. 5. Automatized station for casting piston MFGD (Multi Functional Gasoline Diesel) [7]

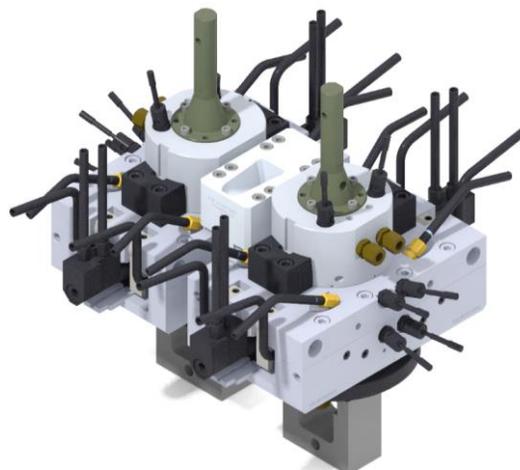


Fig. 6. Model of a modern double permanent mould for piston casting (Gasoline) [7]

According to Figure 6, one permanent casting mould has 8 cooling circuits equipped with numerically controlled electrovalve assemblies. This enables uniform cooling of the casts, coupled with automatic opening and closing of the permanent mould at the technologically pre-set time and temperature. It happens because the system controlling the water circulating in the closed cycle is coupled with the heat exchangers, which regulate the temperature of the nozzles at the entrance and exit of the permanent mould. Such a cooling system ensures a uniform manner of piston cast crystallization and the coupling of their cooling time with the collection of a new portion of the liquid alloy and pouring it into the permanent mould ensures optimal efficiency of the casting process.

4. Changes in piston construction

A range of requirements posed for engine pistons, such as: low mass, high strength at elevated temperatures and higher engine power, have demanded a development of the piston construction. The changes refer to e.g. casting pistons from Al-Si alloys mainly of a near-eutectic composition (Table 1), better cooling of the main piston part through different head shapes, and application of ring inserts and salt cores as well as protective coatings.

Table 1.
Results of the chemical composition of piston Al-Si alloy [%] [7].

Si	Cu	Ni	Mg	Fe
10,5÷11,5	3,0÷4,5	2,0÷2,5	0,6÷1,0	0,2÷0,5
Mn	Zn	Other	Al	
0,1÷0,2	0,04÷0,08	max. 0,02	Residue	

The shape of the head determines the method of swirling the fuel-air mixture and thus the combustion efficiency in the cylinder and the related proper heat removal from the piston. The shape of the piston head, especially in self-ignition engines, determines the type of combustion chamber. In engines with direct ejection, a bigger part of the mixture combusts over the "non-flat" piston

head, and for this reason, the pits made in it facilitate this process (Fig.7). In turn, in engines with indirect ejection (combustion space divided into a turbulence chamber and a precombustion chamber), the piston heads are usually flat or slightly convex for their increased strength (Fig.8).

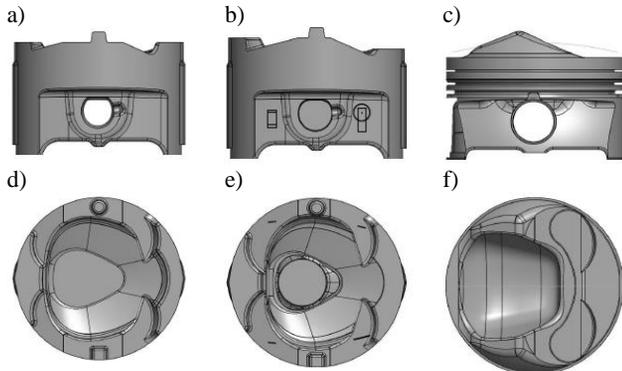


Fig. 7. Exemplary pistons for engines with direct ejection: a-c) side view; d-f) piston head surface [7]

A change has also been made to the internal construction of the piston. This was mainly caused by the necessity of improving the cooling of the main section of the piston and reducing its mass. The insides of the pistons shown in Figures 7 and 8 have been presented in Figure 9.

Piston ring inserts (so-called "alfin" inserts)

In the head of the piston (ring belt section), there are rings, which play two main roles:

- sealing the piston in the cylinder and
- removing the heat from the piston to the cylinder walls.

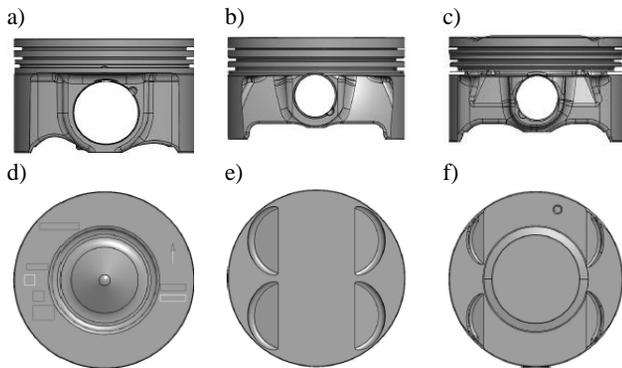


Fig.8. Exemplary pistons for Light Vehicles engines: a-c) side view; d-f) piston crown surface [7]

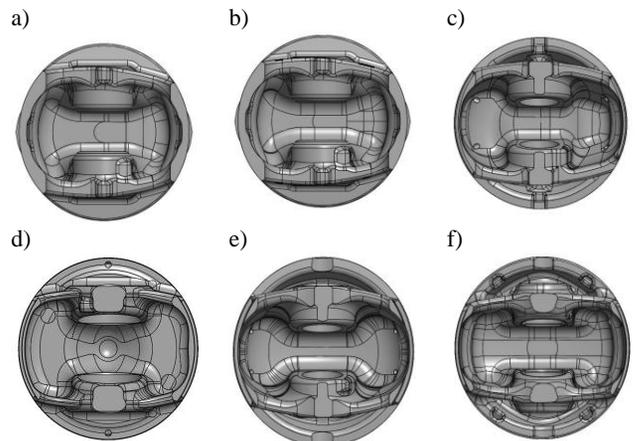


Fig. 9. Internal construction of the present pistons: a-c) pistons from Figure 7; d-f) pistons from Figure 8 [7]

The piston rings (usually 2 or 3 and even 4) are most often made of grey, spheroidal or alloy cast iron with an addition of nickel, chromium and molybdenum. On their circumference, they have a indentation, which enables assembly on the piston and ensures proper elasticity (ring lock). The first rings from the top have a sealing purpose. The middle one plays a sealing (compression-scraping) role. The ring placed the furthest from the piston head scrapes the oil excess from the cylinder walls in order to prevent its access to the combustion chamber.

The proper operation of the piston depends mainly on its thermal expansion and the maintained clearance between it and the cylinder. Too small a clearance causes jamming of the piston after its heating and expanding, while too large a clearance leads to improper positioning in the cylinder and reduced tightness. In order to prevent it, in modern pistons, special ring inserts are used, especially for the upper ring (Fig.10). They constitute reinforcement of the most thermally loaded ring, making it possible to limit as well as control the thermal expansion of the piston skirt. Their drawback is, however, a worsened heat removal to the lower sections of the skirt.

These inserts, made of austenitic cast iron (Table 2), after surface treatment, are subjected to so-called "alfinating" [9-11]. It is a process of short submersion in the Al-Si alloy in order to form a diffusive layer, which increases the adhesion of the ring insert to the piston casting [12].

Table 2.

Results of the chemical composition of cast iron GJLA-XNiCuCr15-6-2 (according to the norm DIN EN 13835) for ring inserts [%] [7].

C	Si	Mn	Ni	Cu
2.4÷2.8	1.8÷2.4	1.0÷1.4	14.0÷17.0	6.5÷7.0
Cr	P	S	Fe	
1.0÷1.6	max. 0,08	max. 0,01	Residue	

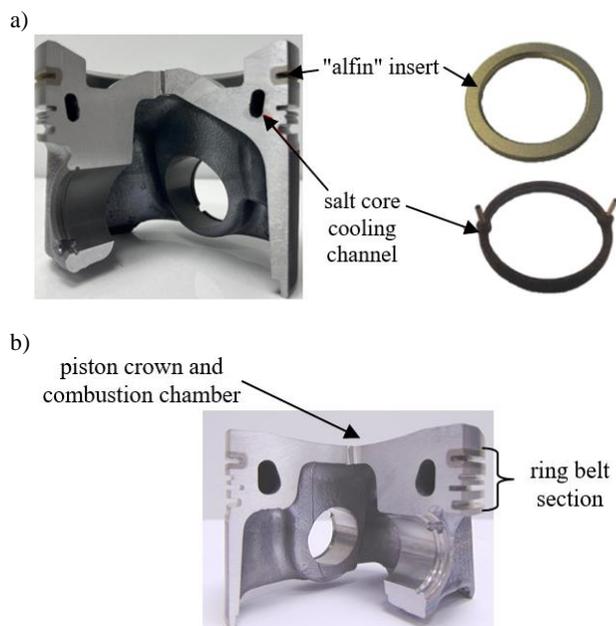


Fig. 10. Modern pistons with a ring insert and a salt core for: a) a Diesel engine, b) a gasoline engine [7]

Salt cores

Salt cores, made by means of the sintering method, consist in 99,9% of NaCl. Salt is pressed under pressure in a die, which represents the final shape of the core. Before being mounted in the permanent mould, the cores are heated to about 450°C, with the aim to avoid stresses, which can damage them during the pouring of the liquid piston alloy. They are fixed on special "pins" (Fig.10), which determine their position with respect to the cast.

At the following production stages, the cores are removed by being washed off with water. After the washing-off, the core reflects the channel in the piston head (Fig.9). During the work of the piston in the engine, the oil circulates under pressure in the channel, thus cooling the piston head and the ring section (especially within the first ring from the combustion chamber). The shape and dimensions of the salt cores depend mainly on the construction of the piston and the requirements of the client.

At the turn of 1980s and 1990s, cooling channels were used only for highly loaded Diesel engines with compression ignition. The present pistons used for gasoline engines are also equipped with cooling channels as well as an "alfin" insert in the ring belt.

Surface treatment of pistons

Pistons after machining undergo various procedures of surface treatment, which usually includes:

- preliminary and inter-operational washing,
- activation washing,
- phosphatizing and manganese phosphatizing,
- graphite covering,
- tinning,
- anodizing,
- chromium plating, etc.

Phosphatizing and manganese phosphatizing (MnP) of pistons (Fig.11)

Phosphatizing of pistons aims at protecting the surface from corrosion and is a form of preparing the piston's side surface for graphite coating. The chemically formed conversion layer with the thickness of up to 1 μm has a very well-developed surface (needles, plates or grains), thus increasing the adhesion of the graphite to the piston. Depending on the addition introduced during the phosphatizing, we distinguish between: phosphate-zinc, zinc-calcium, manganese and phosphate-iron coatings. The corrosion process taking place on the surface of these coatings has the character of electrochemical corrosion. Phosphatizing is applied exclusively for pistons made of aluminium alloys.

Manganese phosphatizing (MnP), in contrast to the "regular" phosphatizing, is applied for steel pistons. The MnP layer absorbs the engine oil very well, causing better protection of the ring grooves and the pin opening from seizing and corrosion during the piston's operation.

The application of the MnP layer is a chemical process. After the mechanical treatment as well as proper preparation of the surface and its drying, MnP crystals are deposited from the water solution. A good quality MnP layer characterizes in a black or dark grey shade (Fig.11d).

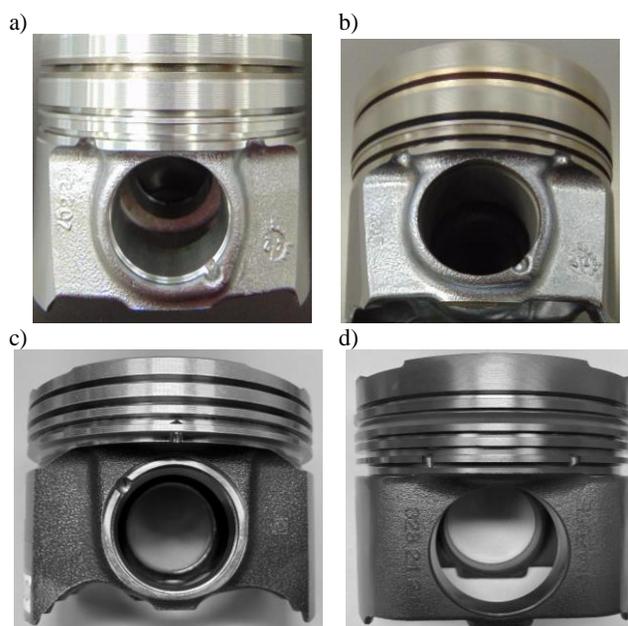


Fig. 11. Pistons for a Diesel engine: a) aluminium before phosphatizing; b) aluminium after phosphatizing; c) steel before manganese phosphatizing; d) steel after manganese phosphatizing [7]

Graphite covering of piston skirt

The graphite covering process of the piston skirt consists in depositing a special phenol resin-based graphite paste onto the properly prepared surface. The graphite deposition takes place by the screen printing method. After a proper shape is deposited (stamped), the pistons are annealed in a furnace, with the aim to network the resin and reinforce the graphite on the piston's surface. The purpose of graphite coating is to form a thin layer on

the surface of the piston (from 5 to about 15 μm), which protects the guide section of the piston and reduces the friction between the piston and the cylinder (Fig.12). The surface layer of the graphite also improves the wettability of the oil and fills all micro-irregularities of the substrate material's surface, which improves the grinding conditions. It ensures a reduced friction force, especially during the expansion stroke, as well as a reduced temperature of the cooperating surfaces, and this protects them at the moment of mixed friction and boundary friction. It protects the pistons skirts from seizing during the engine's breaking-in. Graphite coatings constitute one of the many types of anti-reflective coatings deposited on pistons made of Al-Si alloys.

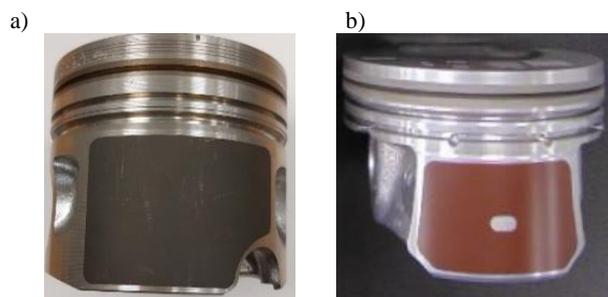


Fig. 12. Piston skirt after graphite covering: a) for a Diesel engine; b) for a gasoline engine [7]

Tinning and anodizing of the piston surface

The tinning process aims at protecting the piston surface from oxidation. The properties of metallic tin provide it with good slide properties, thus reducing the friction in the engine's cylinder. At present, tinning is being replaced with phosphatizing and manganese phosphatizing.

The process of anodizing consists in current oxidation of aluminium in a solution of the appropriate electrolyte. The aim is to form a Al_2O_3 layer with the hardness of over 270 HV and thickness of 10-25 μm . This layer protects the first ring groove from deformation and wear during operation. Anodizing is applied for gasoline engine pistons. In the case of anodizing the piston head, this layer constitutes thermal insulation of the piston material.

Chromium plating

This is the most frequently used method of increasing the hardness of the surface layers of piston ring sliding surfaces and the cylinder bearing surfaces. The layer of chromium protects the cooperating surfaces against cavitation erosion, forming a surface without scratches or microcracks, which could be the source of corrosion and in consequence cavitation pitholes [13]. The most advantageous thickness of a chromium coating is from 20 to 25 μm . A higher thickness does not represent any benefits as it often leads to the deposited chromium being separated from the substrate, causing loss of adhesion. Chromium coatings characterize in a high melting point (about 1920°C), low coefficient of friction, good abrasive and adhesive wear resistance as well as a higher thermal conductivity coefficient than that of cast iron. The hardness and maximal work temperature of chromium coatings equal: from 1800 to 3500 HV and from 350 to 900°C, respectively [13]. The chromium layer should be electropolished and mechanically ground in order to reduce the

effect of imperfections of the formed surfaces, which prevents scratching of the cylinder bearing surface.

Molybdenum coatings

A layer of molybdenum disulfide is deposited by the metal spraying method in oxygen-acetylene flame or by means of a gas burner. MoS_2 coatings have a high melting point (about 2620°C) as well as high hardness (about 1076 HV), which is important during the cooperation of the sliding surfaces of the rings and the piston skirt, as it limits the risk of seizing during the initiation of mixed friction and boundary friction. Pistons with MoS_2 coatings are used in heavily loaded engines, in which the rotational speed is high [13].

Ceramic coatings

They constitute one of the methods of isolating the piston walls from the high temperature of the working factor during the burning of the fuel-air mixture, thus limiting the stream of heat penetration through these surfaces to the subassemblies of the cooling system. These coatings, produced by the plasma spraying method, characterize in high thermal stability and a porous structure of the surface layer. Owing to this, a higher temperature can be achieved in the combustion chamber with a simultaneously lowered temperature of the piston and its rings [14]. Usually, ceramic coatings contain zirconium oxide with an addition of CaO ; MgO ; CeO_2 ; Y_2O_3 ; Ln_2O_3 or Al_2O_3 [12]. The thermal expansion coefficient of these coatings rises with the increase of the temperature of the layer, however, it is about 25 times lower than that of iron alloys and about 75 times lower than that of Al-Si alloys [13].

Dispersion coatings

These coatings, often based on nickel, consist of electrodeposited surface layers of a metallic origin, containing additives of non-metallic powders with high dispersity, e.g. diamond powder, Al_2O_3 ; ZrO_2 ; Fe_2O_3 or carbides: TiC , WC , SiC [15]. Deposited on Al-Si alloy pistons, they characterize in thickness of up to 200 μm , ensuring elevated hardness, abrasive wear resistance and cavitation erosion resistance. At present, more and more often, on the sliding surfaces of piston rings and piston side surfaces, the following are deposited: single-layer coatings, e.g. AlTiSiN , AlCrTiN , AlTiN , TiAlN , TiAlCN , TiCN , mixed coatings, e.g. $\text{CrN}+\text{Cr}_2\text{N}$, coatings with phases ($\alpha\text{-Cr}$, CrN and Cr_2N), multi-layer coatings Ti/TiN , coatings with different surface layer thicknesses CrN/Cr/CrN , TiN coatings based on the NiTi alloy and coatings deposited with the CVD and PVD methods [13].

5. Summary

The automotive producers today aim at improving the general mechanical efficiency of the engine, e.g. by reducing the fuel consumption and harmful substance emission as well as reducing the friction losses of the piston-rings-cylinder system (PRC) and the engine timing gear mechanisms. In terms of piston durability and long inter-repair mileages, the aim is to achieve a compromise between the small mass of the PRC system and its high power and reliability for high operational performance. In the PRC system, it can be achieved mainly by:

- limiting the number of sealing rings,
- optimizing the clearance in the PRC system,
- reducing the height of the piston and its rings,
- changing the profile shape of the piston skirt and the piston ring sliding surface,
- increasing the pressure in the function of piston linear speed and the engine rotational speed with the consideration of the injection pressure of up to 220 MPa, the mean pressure up to 3,1 MPa, the maximal pressure up to 21 MPa, the specific initial power up to 100 kW/l and lower and lower combustion gas emission,
- applying protective coatings with low surface roughness and high abrasion resistance under friction,
- reducing the friction losses by limiting the allowance of the PRC system, with the consideration of the local minimal thickness of the oil film between the piston ring sliding surface and piston skirt and the cylinder bearing surface,
- using piston alloys based on aluminium – reduction of mass and geometrical dimensions with the proper thermo-mechanical load resistance.

The first permanent mould casting machines for piston casting ensured the piston crystallization time (e.g. $\phi 80$ mm) of about 60 s. The possibility to cast only one piston and the lack of process automatization caused the average annual production of aluminium alloy pistons in 1990 to 2005 to be at the level of about 4 million, with a slightly increasing tendency.

After 2001 were Federal-Mogul Company bought WSK Gorzyce, modern integrated lines for piston casting were introduced. Automatization of the main casting tasks and synchronization of the permanent mould casting machines with casting robots ensured high process efficiency. The use of additional water systems shortened the alloy cooling time (to about 13 s and less) and unified the manner of piston crystallization, which increased the number of ready products (Fig.13).

A change has also been made to the piston construction. The current trends in the construction of combustion engine pistons aim at increasing their cost-effectiveness and eco-friendliness through an increase in general efficiency, which at present equals about 52% (earlier about 40%).

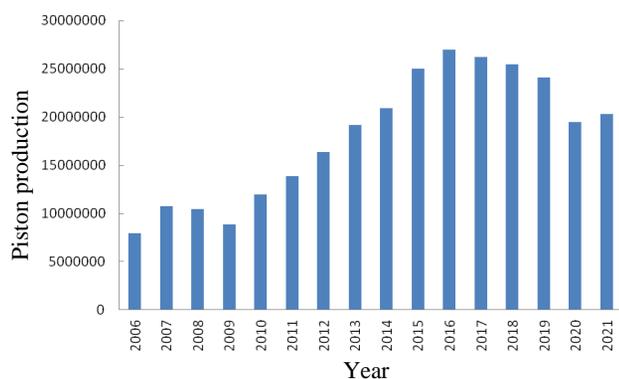


Fig. 13. Piston production at Federal-Mogul 2006 – 2021 [7]

Achieving even better indexes of cost-effectiveness is possible e.g. through an increase of the mechanical efficiency. This efficiency is a measure of friction losses in movable mechanisms of the combustion engine and is at the level of about 70÷80%. It is assumed that the PRC system causes about 50% of total friction losses in the engine and that is why it is justifiable to implement piston solutions which reduce these losses. The latter include e.g. the use of components (salt cores and ring inserts), piston mass and height reduction, coating the piston skirt with protective layers: phosphatizing, graphite covering, tinning, anodizing, chromium plating, etc.

The present efforts of combustion engine piston producers aim at limiting the fuel consumption and CO₂ emission through a compromise between producing engines with reduced cubic capacity and high power, with their maintained durability. This leads to the production of new generation pistons characterizing in low mass, low friction coefficient and increased high temperature resistance, especially within the upper section of the piston (co-called "crown"), where the temperature is the highest and reaches a few hundreds of degrees Celsius. The use of cooling channels, alfinated ring inserts and different geometries of the piston head have caused the present pistons to demonstrate increased strength (especially important in modern engines with high compression ratio) and reduced piston crown temperature by about 25÷30°C compared to the temperatures present on the piston crowns produced in 1980s and 1990s. Lowering the crown temperature has the key importance in terms of prolonging the piston durability. Moreover, the application of ring inserts has lowered the temperature of the upper ring below 250°C, which helps limit the oil consumption.

The high values of pressure present in the cylinder and the thermal loads resulting from the high unit power require the use of advanced piston production technologies. A special case are pistons in supercharged Diesel engines, which characterize in high thermo-mechanical loads. This results from the large surface area of heat transfer from the combustion gases, the intensity of the heat transfer caused by the vortex flow of the load in the cylinder and the fuel-air mixture combustion time.

In order to ensure it, in silumin piston casts, local, often laser, remelting of the combustion chamber edges as well as rapid cooling are applied, which leads to achieving a fine-grained crystalline structure. This technology makes it possible to obtain a structure of solid solution $\alpha(\text{Al})$ and refinement of silicon crystals (β) from about 50 to about 5 μm [16]. This helps increase the crack resistance of the piston head edges. Owing to this process, it is also possible to increase the piston temperature in the area of combustion chamber edges to the value of about 420°C.

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