

Optimization of the combustion chamber strength of aluminum pistons in diesel engines using the DuralBowl technology

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The article focuses on the problem of loading the combustion chamber of diesel engine pistons together with the method of its optimization using the DuralBowl technology. Along with the growing requirements of exhaust emission standards, the increasing competition in the efficiency of internal combustion engines, the load on the combustion pistons increases due to the increase in pressure and temperature of fuel combustion and the tendency to slim the structure. Numerical analyzes and analyzes of damaged pistons in diesel engines have shown that one of the places most exposed to piston damage are the combustion chambers. There is a concentration of thermomechanical stress at the edge of the combustion chamber, which may lead to the destruction of the piston and the necessity to carry out overhaul of the drive unit. One of the technologies that optimizes the strength of this zone is the DuralBowl local remelting process. This process allows for several times improvement in the fatigue strength of pistons in internal combustion engines. The article analyzes the thermomechanical load on the combustion chamber along with the impact of this load on the durability of pistons in diesel engines. An analysis of the DuralBowl process was also performed, aimed at eliminating the negative effects of loading the combustion chamber, extending the piston life. The analysis focused on the microstructure of the material before and after the DuralBowl process.

Key words: diesel engines, DuralBowl, piston, combustion chamber, chamber melting

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1. Introduction

The rapid development of the automotive industry determines the search for newer directions in the development of car components and the technology of their production at the designers of cars with internal combustion engines. In addition, there is a tendency to constantly increase the performance of the internal combustion engine, which forced the creation of more effectively working pistons of internal combustion engines through the use of more durable materials, better technological treatments and by improving the engine operating conditions [1]. It is one of the factors determining the market success of the engine and the possibility of its use on world markets. Its ability to reduce the harmfulness to the environment by meeting the required exhaust emission standards is fundamental for its admission to global markets. Over the years, exhaust emission standards have changed to reduce the limits of toxic exhaust gas components, fuel consumption, and lengthening the life cycle of the engine [2]. Optimization of new design and operation solutions for internal combustion engines is often associated with increasing thermal and mechanical loads on the elements surrounding the combustion chamber of the internal combustion engine. One of the significant factors affecting the strength of the internal combustion engine components and the degradation of the oil film is the thermal load [3]. By using more durable materials is meant replacing aluminum alloys with alloy steels or ductile iron. You can also influence technological procedures, i.e. the use of coatings, changes in the structure of the material, heat treatment, change of the surface of the pistons. Assuming staying with aluminum alloys in the production of pistons of internal combustion engines, the use of coatings and influ-

encing the structure of the material are particularly interesting, as is the case with the DuralBowl technology. It allows you to improve fuel efficiency and minimize exhaust emissions from diesel engines [4].

The piston of diesel engines is expected to withstand thermal and mechanical loads, correct thermal conductivity, resistance to high temperature gradient, low friction coefficient, low weight. The most popular material in internal combustion engines is aluminum alloy. It owes its popularity to low weight, low production cost and sufficient resistance to the conditions in the engine cylinder. As the requirements increase, diesel engines are increasingly loaded, which leads to the operation of the pistons at the limit of their endurance [5].

2. Combustion chamber damage analysis

One of the most stressed parts of the piston is the combustion chamber which is most exposed to pressure and temperature. Many studies present the edge of the combustion chamber as a stress build-up [6–8]. The deformations due to pressure are different in the main plane of the piston along the pin bore than in the plane perpendicular thereto. With proper engine operation, the force reaches 60,000 N for passenger cars and up to 360,000 N for trucks. However, these forces can be even twice as high if the internal combustion engine is not working properly. As a result, in diesel engines, cracks and chipping may appear on the piston crowns [9]. For a better illustration of the zones most exposed to destruction, Fig. 1 presents a numerical analysis of the temperature gradient of a piston in a diesel engine. It shows that the rim of the combustion chamber is the place of concentration of thermal intensities, the most vulnerable to damage.

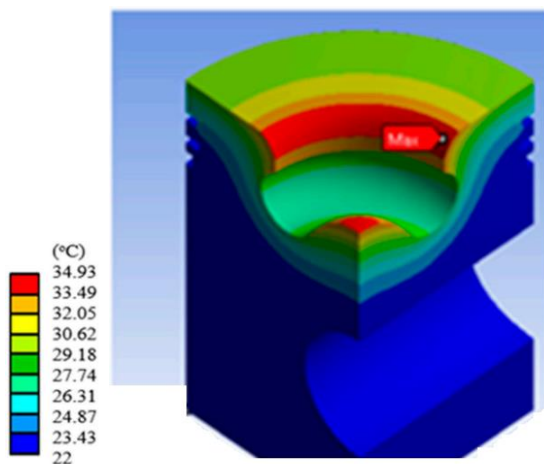


Fig. 1. Numerical analysis of the temperature gradient of a piston in a diesel engine [10]

Of course, the influence of high temperature on the rim of the combustion chamber of diesel pistons can be eliminated by changing the engine operating parameters, changing the piston material, changing the piston structure, etc. One of such design changes is the addition of a cooling duct, as shown in Fig. 2. This design change was introduced, caused that about 50% of the heat from the piston is dissipated through the cooling channel, and to a much lesser extent is dissipated by the piston ring part. The addition of a cooling channel to the piston of the diesel engine also reduced the maximum temperature of the rim of the combustion chamber by approximately 30 degrees. The temperature of the working medium in the combustion process can reach even 2000°C [11]. However, with increasing environmental requirements, increasing combustion pressures and temperatures, the addition of a combustion chamber may not be sufficient to provide the required strength for aluminum diesel pistons. Other possible design changes of the combustion chamber are shown in Table 1, together with the determination of their influence on the durability and performance of the piston.

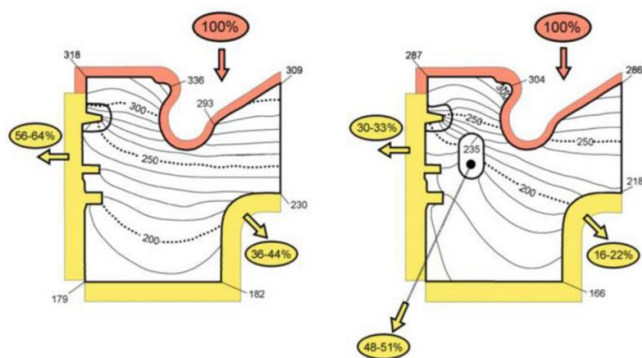


Fig. 2. Temperature distribution of the combustion chamber of a diesel engine piston with and without a cooling channel [11]

Stress concentration in the bottom area results in numerous failures and damage to the pistons, often resulting in engine stoppage and the need for a major overhaul. The most common types of damage include: chipping, cracks, melting, which are very often the result of improper engine

operation. Figure 3 shows the piston of a diesel engine with a damaged edge of the combustion chamber. The damage was caused by thermal fatigue associated with material stress caused by a change in the thermal gradient of the piston. The thermal stresses in the piston result from the difference in temperature across the piston crown with the flow of hot gases and the impact of the fuel. The edge of the combustion chamber is an area of elevated temperature, and the thermal deformation of this area is limited by the surrounding piston material, which causes significant compressive stresses over the entire area of the combustion chamber, often exceeding the yield strength of the piston material. After relaxation of the compressive stresses of the cold piston occurs, the creep effect causes an increase in the tension of the residual stresses at the edge of the combustion chamber. The occurrence of these cyclic stresses causes fractures of the edges of the combustion chamber.

Table.1. Influence of changes in individual features of the combustion chamber of a piston of a diesel engine [10]

Parameter	Effect
Bowl depth	Reduce emissions of soot, hydrocarbons, carbon, monoxide, nitrogen oxides and specific fuel consumption [13]
Throat diameter	Reduce specific fuel consumption and increase crushing [14]
Bowl diameter/depth ratio	Increase crushing, improve air fuel mixture, and generate higher efficiency [15]
Lip radius	Increase performance and reduce the generation of polluting emissions [16]
Outside diameter	Decrease throat diameter ratio to increase swirl and increase turbulence [17]
Protrusion height	Reduce emissions of nitrogen oxides [18]
Bowl diameter	Reduce the generation of smoke and generate greater crushing [19]



Fig. 3. Diesel engine piston with a chipped edge of the combustion chamber [20]

Figure 4 shows the piston of a diesel engine with a crack at the bottom from the combustion chamber to the shell in the plane of the bolt hole. The crack originated in the piston's combustion chamber. In pistons with a combustion chamber on the inner edge of the combustion chamber, there are two stress concentration areas in the plane of the pin bore.



Fig. 4. Diesel engine piston with a crack on the bottom [21]

Figure 5 shows a diesel engine piston with a melted bottom. This type of damage occurs most often in direct injection diesel engines. It was created as a result of not maintaining the proper injection pressure, which causes vibrations that can raise the needles again, allowing the fuel to enter the combustion chamber. Then, after the remaining oxygen is used up, the fuel droplets flow to the piston crown, where they burn at high temperature, causing the piston crown material to soften. Erosive and mass forces acting on the fast-flowing exhaust gas tear particles of the softened material from the piston crown.



Fig. 5. Diesel engine piston with a melted bottom [21]

3. DuraBowl process analysis

The combustion process in diesel engines takes place in the combustion chamber, where the pressure can reach over 200 bars and the temperature over 400 degrees. The presented analyzes of thermal and mechanical damage have shown that the rim of the combustion chamber is particularly vulnerable to damage. By analyzing the microstructure in this area, the presence of free silicon particles decomposed

on aluminum can be detected. It should be noted that aluminum expands eight times more than silicon, which causes stresses inside the piston material as the temperature changes. Repeated heating and cooling of the piston material by ignition in the cylinder can fatigue the combustion chamber material. This type of failure is referred to as thermomechanical fatigue due to excessive high and low cycle fatigue loads. That is why Federal Mogul has developed the DuralBowl technologies, which place particular emphasis on the local improvement of the microstructure of the combustion chamber rim in order to improve the strength of the aluminum piston and increase the resistance to multiphase thermomechanical fatigue load. Diesel pistons are subjected to a low-cycle thermal load and a high-cycle mechanical load due to a combustion load per engine cycle.

The DuraBowl technology enables about ten times greater fragmentation of the microstructure than in the case of the cast structure. The fragmentation of the structure significantly improves the fatigue strength of the optimized combustion chamber surface. Validation tests of pistons with a remelted chamber and without remelting have shown an increase in service life from 4 to 8 times [22]. The increase in strength of aluminum pistons makes it possible to ensure sufficient strength despite increasing ignition pressures and temperatures in the fuel combustion process. The process itself can be described as a local process of remelting critical zones of the combustion chamber with a modified form of tungsten inert gas welding. The DuraBowl process is performed by a welding robot with strictly defined process parameters.

The smelting process requires one pass if only the edges of the combustion chamber are to be strengthened, and the base of the chamber also needs to be strengthened several times. Rapid heating of the piston surface by a welding robot using the TIG method and then its very rapid cooling causes fragmentation of the microstructure of the melted chamber surface. Figure 6 shows simulations of smelting the edge of the combustion chamber of a piston in a diesel engine.

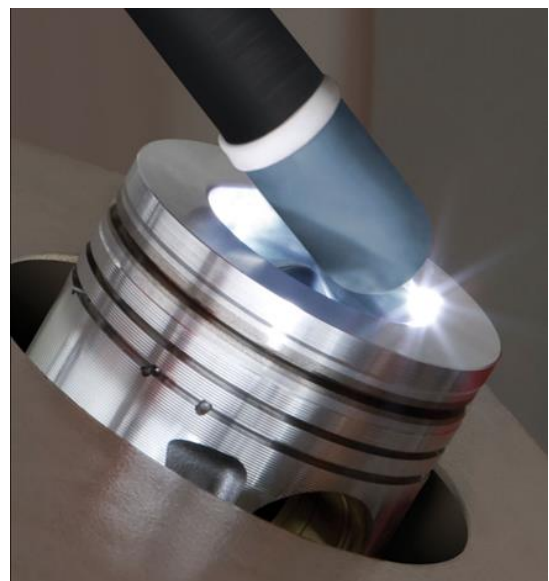


Fig. 6. Simulation of the fistula at the rim of the combustion chamber [22]

Figure 7, 8 shows the edge of the combustion chamber of an aluminum piston before and after the local DuralBowl remelting process. Figure 7 shows the combustion chamber before local remelting. It is a roughly machined piston. Figure 8 shows the same piston, but after the local melting of the combustion chamber edge. You can see the surface change caused by the TIG melting method. The surface is smooth, uniform without any discontinuities. The following parameters play the most important role in this process: current type and intensity, arc voltage, welding speed, type and flow rate of shielding gas, diameter, shape and type of non-consumable electrode, balance and frequency of current, method of cooling. Appropriate selection and stability of these parameters guarantees obtaining the appropriate structure of the melted material.

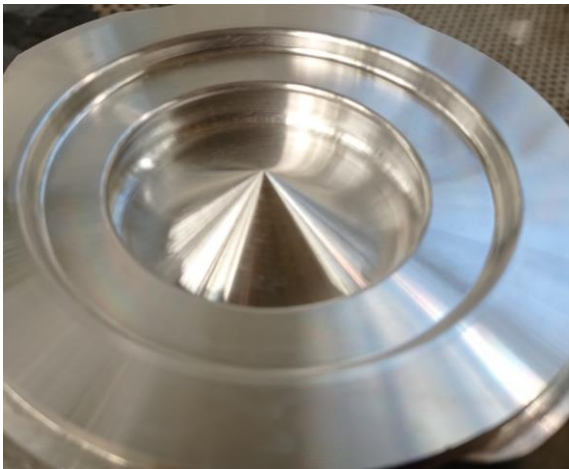


Fig. 7. Combustion chamber of an aluminum piston before the local DuralBowl remelting process



Fig. 8. Combustion chamber of an aluminum piston after the local DuralBowl remelting process

Figure 9 shows the structure of the melted rim of the piston combustion chamber. The depth of the penetration is about 3 mm in depth. The transition of the fragmented microstructure into the native material of the piston casting is smooth. The hardness measured on the Brinell scale in the remelted zone is about 140 HB, while in the zone of the piston parent material it is about 110 HB.

The comparison of materials before and after the DuralBowl process showed that the microstructure of the alu-

minum piston casting material after the remelting process is ten times smaller than the microstructure of the remaining casting. The microstructure of the silicon and intermetallic phases was fragmented. The silicon phase in the piston casting has a size of 50 μm, after the DuralBowl process, the microstructure of the silicon phase is 4–5 μm. Figure 10 shows the transition of the microstructure of the melted rim of the combustion chamber into the microstructure of the native casting of the piston. On the left side of the drawing you can see the microstructure of the casting, while on the right side the fragmented microstructure after the local remelting of the DuralBowl process.

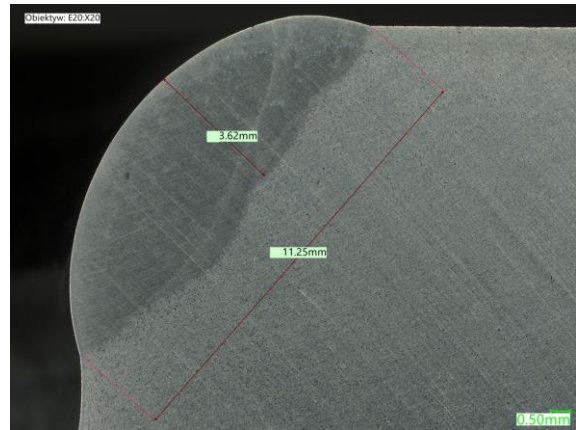


Fig. 9. cross-section of the rim of the melted combustion chamber

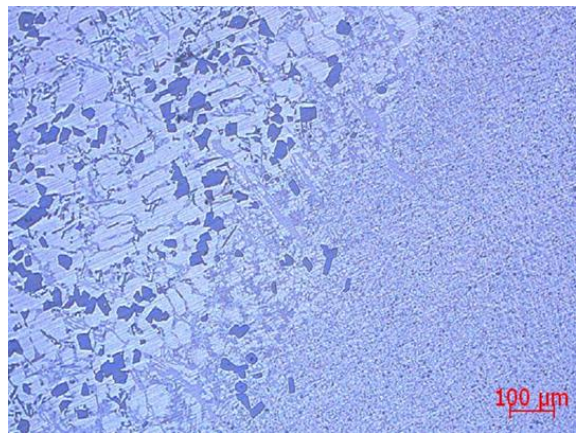


Fig. 10. DuralBowl remelting microstructure

The fatigue strength tests to temperature changes showed that the change of structure in the DuralBowl process increased the resistance to microcracks and microplasticity caused by sudden changes in the operating temperature many times over. This is due to a mismatch in thermal expansion between the aluminum alloy phases of the pistons of internal combustion engines. The differences in thermal expansion between the phases are eight-fold, which causes fatigue in the event of a sudden temperature change [23].

Conclusions

The growing requirements of customers regarding the efficiency of combustion engines and exhaust emissions

have forced engine designers to design new construction solutions working at the limit of their endurance. The operating pressure and the fuel combustion temperature are increased. As a result, aluminum pistons, especially in diesel engines, work at the limit of their strength. Numerical analyzes and analyzes of damaged pistons have shown that the area most vulnerable to damage to the piston of a diesel engine is the edge of the combustion chamber. It is subjected to the highest thermal and mechanical loads.

In order to meet these growing requirements, it was necessary to introduce changes in the structure of aluminum pistons or the technology of their production. Changing the material is not always advisable as steel is much heavier and economically more expensive to produce. Therefore, in order to improve the strength of aluminum pistons in diesel engines, a team of engineers at Federal Mogul developed the DuralBowl technology, which consists of pretoping the

rim of the combustion chamber. The much higher cooling speed than in the casting will make the microstructure of the melted rim much smaller than in the rest of the aluminum piston. The change in structure results in an increase in hardness and resistance to thermal and mechanical microcracks. Melted combustion chamber pistons in diesel engines are more durable and reliable than standard pistons.

In the current application, the DuralBowl local remelting technology is used especially for large aluminum pistons for diesel engines. However, a significant increase in the requirements of exhaust gas standards results in increasing the pressure and temperature of fuel combustion in passenger cars. For this reason, part of the market for aluminum pistons has been replaced with steel pistons, however, in the further part aluminum pistons show great development potential, supported by new technologies such as DuralBowl.

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