ANALYSIS OF AN AUTOMOTIVE PISTON USING FINITE ELEMENT METHOD

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This article presents a finite element analysis of a piston with the same coordinates, made entirely of different materials: steel (SAE-AISI 4140) and aluminum alloy (EN AC-48000). The purpose of the analysis is to choose the most suitable material for making the engine piston using the finite element method (FEM). A comparative study of relevant parameters for each material was carried out: applying the same force, the piston's behavior was studied at thermal stress. By modifying the application point (height from the piston head) the effect on the piston shape for the two chosen materials was analyzed. CATIA V5 (Computer Aided Three Dimensional Interactive Applications), a product of Dassault Systèmes, which is currently one of the most widely used CAD systems, has been used to perform the analysis.

Keywords: piston, deformation, finite element analysis, mechanical properties.

1. Introduction

Piston engines are one of the most complex components of all automotive components in industry or other industrial fields. The piston is the most demanding organ of an internal combustion engine due to its high pressure and high temperature operation. The piston has an alternate movement in a cylinder that closes a variable volume, filled with pressure vapor (fuel, fluid or fluid

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mixture). The piston is used to convert internal energy into mechanical work (car engine) or vice versa, for generators. Usually the piston is coupled to a crank mechanism that turns the rectilinear motion into a circular motion (on motors) and vice versa (at pumps). The piston (Fig. 1) is used as a construction element in the manufacture of piston pumps, which resembles a principle of operation with the compressors [1].

Fig.1. Components of a piston [1]: 1 - the piston head; 2 - port-segment region; 3 - the piston skirt.

On a free eye examination the shape of the piston seems cylindrical, but in reality the piston is slightly oval. Pistons are made of metallic materials: aluminum, steel and in some cases cast iron. Because these materials have a thermal expansion coefficient, it is clear that the dimensions of the piston are not fixed but variable, depending on the temperature. Thus, in order for the piston to move in the cylinder, there must be a space between the piston and the cylinder, which is higher when the engine is cold and decreases as the temperature rises [2].

The piston head is the most demanding area from the thermal point of view because it comes in contact with the combustion gases and at the same time assumes the pressure forces. Depending on the type of internal combustion engine (gasoline or diesel), the piston head has different shapes: flat, bulging or containing part of the combustion chamber. The port segment region contains three channels in which the segments are mounted. The first segment, closest to the plunger head, is called the compression / fire segment (a), the second segment is called sealing segment (b), and the third segment of the lubrication / tiller (c). The connection of the piston rod is performed with the help of the bolt mounted in the shoulders of the piston also called bolt dwellings (d) [2, 3].

The mechanical energy generated by combustion of the fuel mixture in internal combustion engines is achieved by a series of thermo-chemical processes that take place in the combustion chamber [3, 4].

1.1. Differences between pistons used in diesel and gasoline engines

A diesel engine is distinguished by the fact that the gas pressure in the cylinder is much higher than that of a gasoline engine. For gasoline engines the maximum pressure is around 60 - 90 bar while for diesel engines it reaches 130 to 160 bar. This requires diesel engines to use mechanical parts that have a much higher resistance [4]. Even though an aluminum piston has lighter weight than a steel one, it has been possible to obtain a steel piston of similar size and weight with an aluminum piston. Reducing mass and fuel consumption (2-3%) was possible due to significant differences from the aluminum version [5]:

- reducing the height of the piston head;
- using a longer rod which has an impact on the reduction of side forces;
- reduction of the piston skirt;
- optimization of the piston shape;
- reduction of mounting gaps due to less thermal deformation of steel.

The low height of the steel piston allowed it to be used on motors with the block height too low. The piston is provided with a cooling channel that allows heat transfer from the piston's head through the oil. The piston is made of a single block of material by forging. The use of steel has made it possible to optimize the shape of the piston, which has led to the reduction of blow-by gas losses and oil consumption.

2. Materials and methods

2.1. Finite element analysis of an aluminum piston and an steel piston

Finite Element Method (FEM) or finite element analysis (FEA) is based on the idea of building an object relatively complicated, but simple modules. With a wide field of use, the finite element method (FEM) analysis is a powerful technique way, with the possibility of application in mechanical engineering to determine the stress and deformation state of the solid bodies [6].

2.2. The program used to model the piston

CATIA V5 (Computer Aided Three Dimensional Interactive Applications), a product of Dassault Systèmes, is currently one of the world's most widely used CAD systems with applications in a variety of industries, from the machine building industry to the aerospace and automotive industries [6, 7].

2.2.1. How to use the CATIA program to design the piston

Piston damage has different origin and is mainly wear, temperature and fatigue. But more than wear and fatigue, piston damage is mainly due to the development of stress, namely - thermal stress, mechanical stress. This article describes the stress distribution on the internal combustion engine piston by using

FEA through CATIA 5 software [8, 9, 10, 11, 12]. The main objectives are to investigate and analyze the thermal stress and the mechanical stress distribution of the piston at the actual state of the engine during the combustion process. Studies by analyzing the finite elements on the behavior of different materials were also presented in several works [13, 14, 15, 16, and 17].

The type of analysis performed is based on the static linear elasticity analysis. The structure must meet the requirements for stress, deformation and effort required. For this, the two pistons in Figure 4 (a and b) are modeled in the CATIA Part Design module (used in the construction of three-dimensional mechanical parts), which in this case applies as an alloy material (EN AC - 48000) and a steel (SAE-AISI 4140) to observe the deformation difference when a 200 Pa pressure is applied to the piston head and subjected to a temperature of 300°C. The values used are for a correct example of deformations in terms of pressure and temperature on the piston.

In the CATIA static analysis mode will be established and in the present case we have chosen: the finite element size of 4 mm, the minimum tolerance of 1 mm and the element type – parabolic. On the support surface, the "clamp.1" restriction is applied, and on the upper surface a pressure of 200 Pa as can be seen in Figure 5.

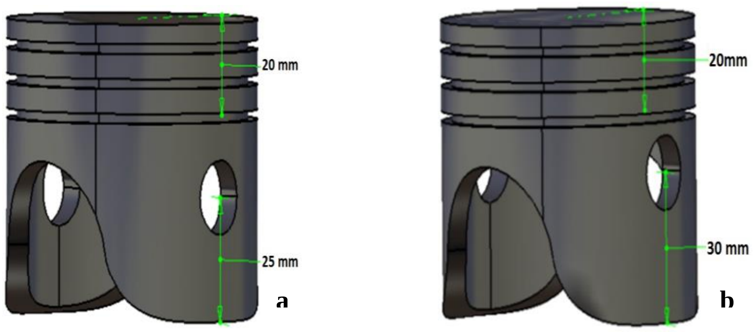

Fig.4. Pistons designed in CATIA: a) pin position at 25 mm; b) pin position at 30 mm

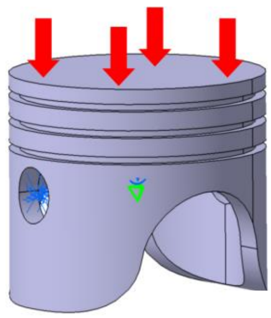

Fig.5. The area were the pressure is applied in CATIA

To perform the static temperature analysis, select the "temperature field" function and import the corresponding values from the Excel format. The maximum temperature used in the analysis is 300°C. The temperature at the center of the piston's head is considered to be 300°C and decreases towards the edge.

In order to determine the stresses due to the maximum pressure in the cylinder, the plunger head is considered to be a circular plate embedded in the contour of the inner diameter of the head, with a constant load (in this case 200 Pa) uniformly distributed. In such a plate, normal radial stresses and normal circumferential stresses occur, and the extreme stresses are obtained in the center of the plate.

3. Experimental results and discussion

3.1. Comparative characteristics of the two materials used in modeling

The two materials (SAE-AISI 4140 and EN AC - 48000) have advantages and disadvantages as we have mentioned earlier. Referring strictly to the comparative characteristics in terms of composition, there are 9 significant properties for both materials. Table 1 shows the differences between the common properties of the two materials.

Table 1.

The physic-mechanical properties of the two materials [1]

Properties	SAE-AISI 4140	EN AC-48000
Brinell Hardness	200-310	100-120
Density	7.8 g/cm^3	2.7 g/cm^3
Elastic modulus	210 GPa	82 GPa
Elongation at break	16-26 %	1.0 %
Poisson's Ratio	0.29	0.33
Specific Heat Capacity	450 J/kg·K	860 J/kg·K
Strenght to Weight Ratio	85-140 kN·m/kg	82-110 kN·m/kg
Yield Tensile Strength	660-990 MPa	230-320 MPa
Thermal expansion	12 µm/m·K	20 µm/m·K

As can be seen, the two materials have significantly different densities. This means that it requires increased attention when interpreting data because some material properties are based on mass units while others are based on surface or volume units. The chemical composition of the two materials used can be seen in Table 2.

Table 2.

Chemical composition [1]

Materials	SAE-AISI 4140	EN AC-48000
Al	-	80.4-87.2 %
C	0.38-0.43 %	-
Cr	0.8-1.1 %	-
Cu	-	0.8-1.5 %
Fe	96.8-97.8 %	0-0.7 %
Mg	-	0.8-1.5 %
Mn	0.75-1.0 %	0-0.35 %
Mo	0.15-0.25 %	-
Ni	-	0.7-1.3 %
P	0-0.035 %	-
Si	0.15-0.35 %	10.5-13.5 %
S	0-0.040 %	-

Ti	-	0-0.25 %
Zn	-	0-0.35 %
Residuals	-	0-0.15 %

3.2. Analysis and results of steel and aluminum pistons

The present study aims to analyze the state of stress using the Finite Element Method to prove the importance of this method in preventing the occurrence of cracks under a certain force exerted on the same piece made of different materials. In the automotive field, the FEM is a particularly useful tool since it can easily be used to help with the maximum stresses supported by the parts in order to optimize the materials used (composition of materials).

In the Figs. 6-9, can be observed the stresses of the parts that were subjected to the specific applied force (200 Pa) can be seen, and in Figs. 10-13 the deformations produced at 300°C, with the insight that all the figures are shown graphically exaggerated for an explicit view.

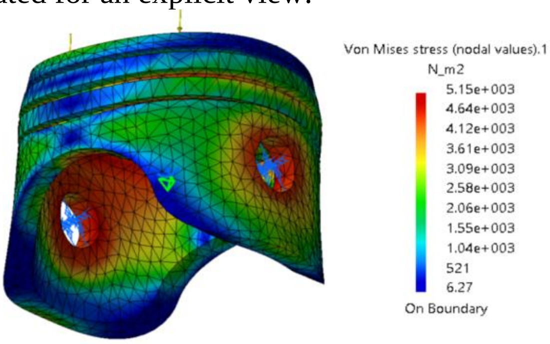

Fig.6. Von Mises stress at the pressure of 200 Pa for EN AC-48000 (pin position at 25 mm)

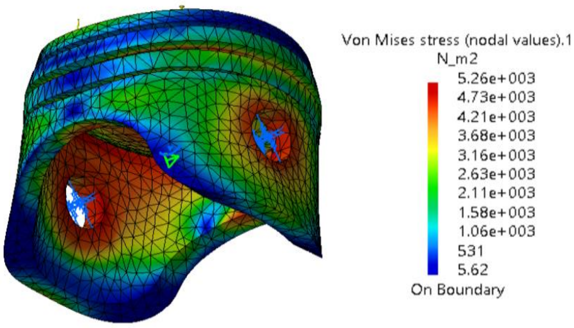

Fig.7. Von Mises stress at the pressure of 200 Pa for SAE-AISI 4140 (pin position at 25 mm)

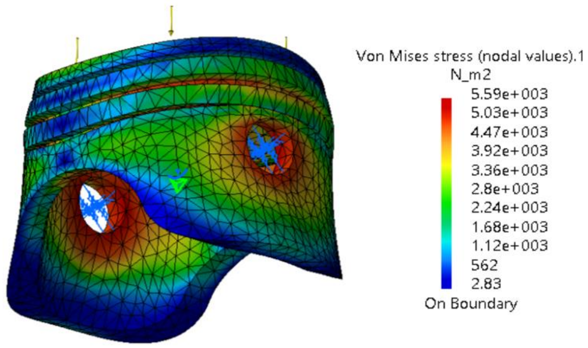

Fig.8. Von Mises stress at the pressure of 200 Pa for EN AC-48000 (pin position at 30 mm)

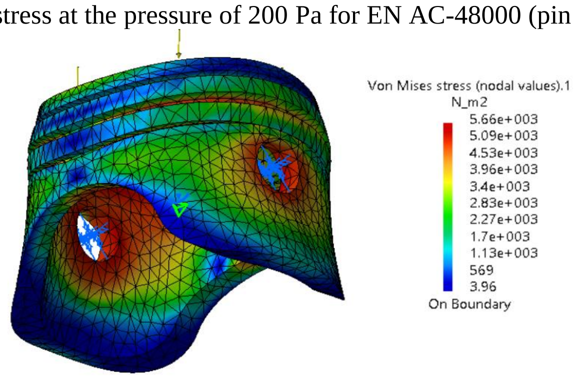

Fig.9. Von Mises stress at the pressure of 200 Pa for SAE-AISI 4140 (pin position at 30 mm)

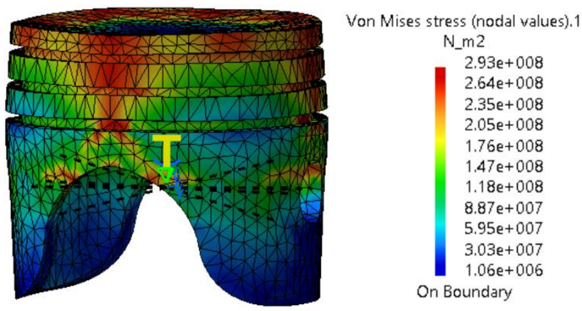

Fig.10. Von Mises stress at the temperature of 300°C for EN AC-48000 (pin position at 25 mm)

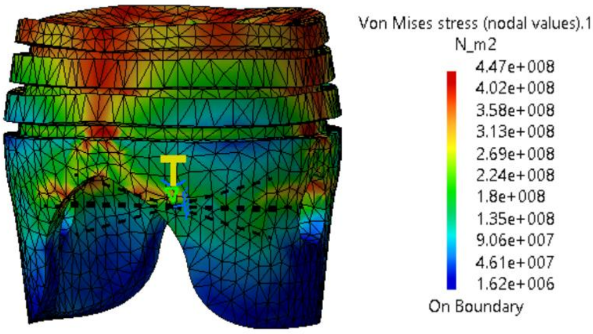

Fig.11. Von Mises stress at the temperature of 300°C for SAE-AISI 4140 (pin position at 25 mm)

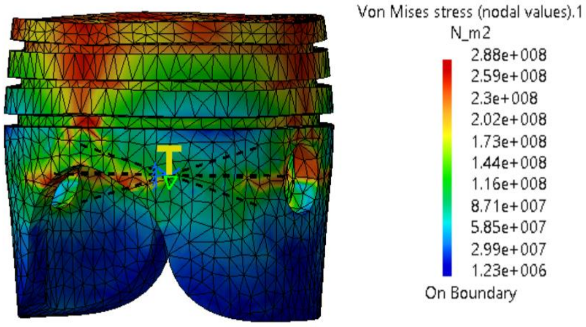

Fig.12. Von Mises stress at the temperature of 300°C for EN AC-48000 (pin position at 30 mm)

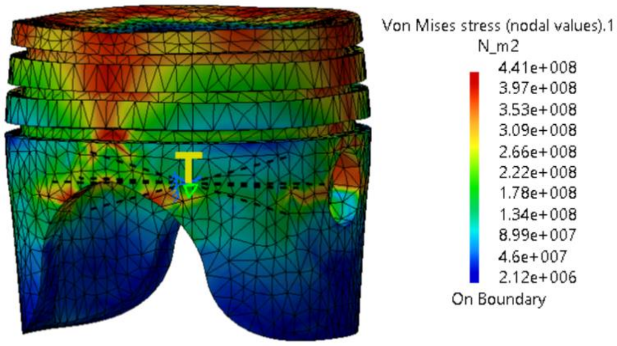

Fig.13. Von Mises stress at the temperature of 300°C for SAE-AISI 4140 (pin position at 30 mm)

In Table 3 we can see the comparative results of stress test performed on the piston to obtain the value and the parameters at which the piston would be damaged. For this analysis, pressure and thermal stress were used as stress parameters, which are the stress that occurs as a result of thermal expansion of structural metallic elements when the temperature changes.

Table 3.

Comparative results between the two materials following deformation at T = 300°C and an applied pressure of 200 Pa

	SAE-AISI 4140 steel	EN AC-48000 aluminium	Relative difference to aluminum, %
Piston mass / kg	0.670	0.241	178 %
Stress (Von Mises) at 200 Pa (pin position at 25 mm), [MPa]	526	515	2.14 %
Stress (Von Mises) at 200 Pa (pin position at 30 mm), [MPa]	566	559	1.25 %
Thermal stress (Von Mises) at 300°C (pin position at 25 mm), [MPa]	447	293	2.56 %
Thermal stress (Von Mises) at 300°C (pin position at 30 mm), [MPa]	441	288	53.13 %

Thermal stress are difficult to simulate because there are two types of thermal stresses in a piston:

a) *Thermal stress due to the vertical distribution of temperature along the high piston temperatures at the top and lower bottom temperature*. There is a homogeneous and constant temperature gradient in the radial direction along the component head. It is noticed that the upper surface of the piston is the area where the temperatures are higher. The thermal deformations in the upper part of the piston are constrained by the surrounding material, causing high compressive stresses on the total circumference of the piston, which often exceed the yield strength of the material.

b) *Thermal demand due to different piston head temperatures due to hot gas flow or fuel displacement*. This distribution causes localized heated areas. The mechanism under which the thermal cracks are formed is the same as that mentioned in (a), except that in this case, these warmer areas will have higher compressive stresses - followed by creep - followed by higher tensile stresses when the piston is cool.

The analysis was carried out step by step with the pressure rising from 50 to 50 Pa - to observe that the difference in the maximum values between the two materials increases as the pressure increases. It can also be seen that the piston whose pin end is closer to the piston head (Figure 4-b) has a higher resistance to the applied pressure, but at the used temperature it has a lower resistance.

In the following graphs the stresses of the two pistons can be observed depending on the applied pressure and what the values are based on the material.

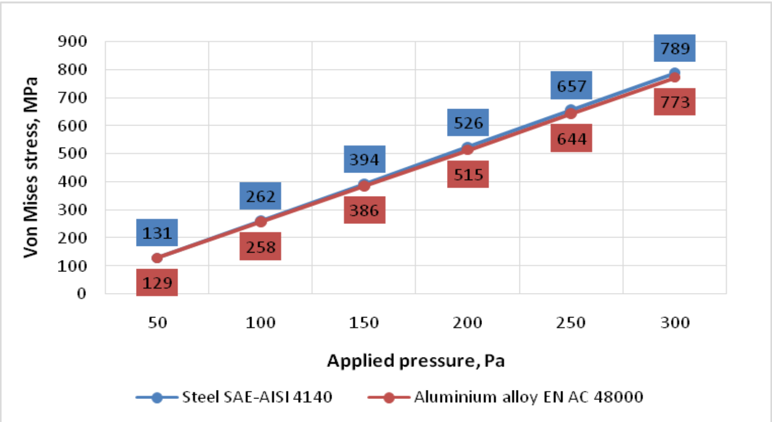

Fig.14a. Values of Von Mises stresses depending on pressure applied to aluminum and steel (Fig.4-a, 25mm)

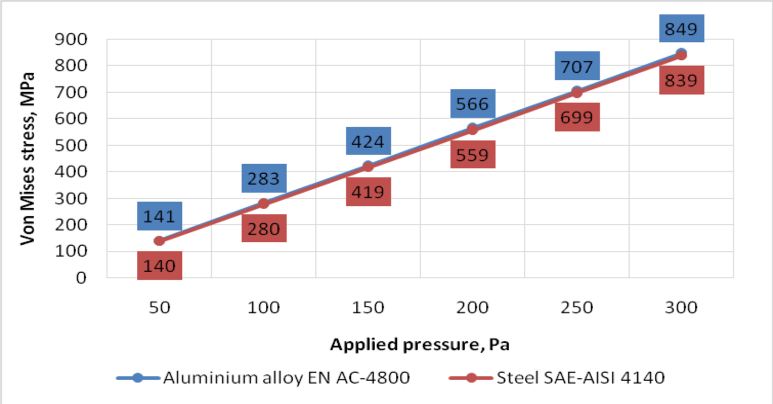

Fig.14b. Values of Von Mises stresses depending on pressure applied to aluminum and steel (Fig.4-b, 30mm)

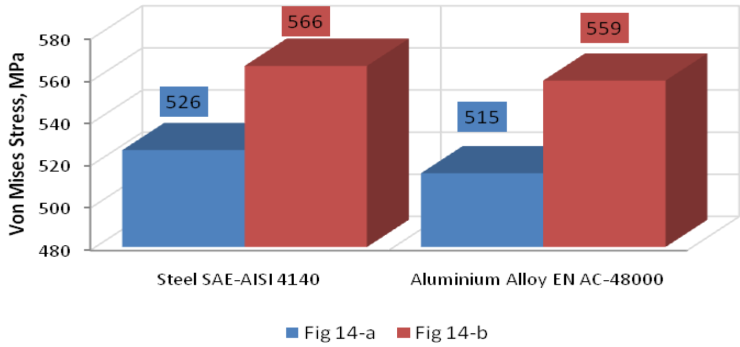

Fig.15. The comparative analysis of the maximum stress (von Mises) for Steel and Aluminum at an applied pressure of 200 Pa, evaluating the results of the two piston variants in Figs. 14(a, b)

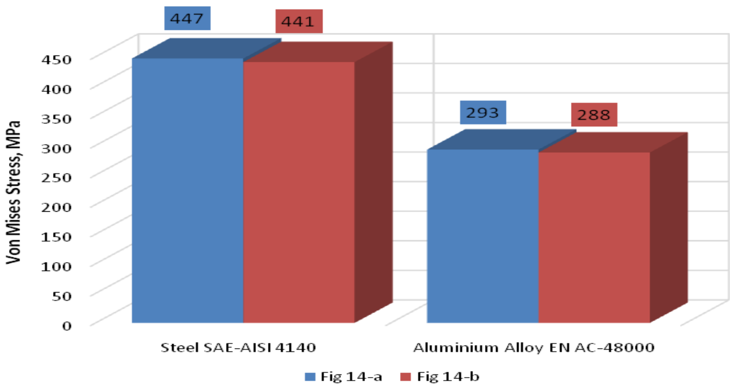

Fig.17. Comparative stress analysis (von Mises) for Steel and Aluminum at an applied temperature of 300°C, evaluating the results of the two piston variants in Figs. 14(a, b)

4. Conclusions

1. The performances of personal computers has led to the design and implementation of new modeling, analysis and synthesis programs for subassemblies, elements and / or machine parts. These high-performance programs are based on numerical methods, of which the FEM was imposed as a numerical simulation method in engineering (design). FEM use attractive and useful graphical interfaces to process input data or interpret the results, being integrated with CAD/CAM applications. CATIA V5 is currently one of the world's most widely used CAD systems with applications in a variety of industries. This program has been used in stress analysis of pistons made up of two different materials. Aluminum pistons are used for automotive engines because they have low weight and can be easily machined. However, aluminum pistons have a weak point, namely the thermal and mechanical loading. In order to increase the power of diesel engines further, steel pistons have been developed which can withstand over 136 hp / liter and cylinder pressures of over 200 bar, and from the point of view of consumption and pollutant emissions they are at the level of aluminum pistons.

2. The steel SAE-AISI4140 used to manufacture the piston has the advantage of low thermal expansion and high resistance to high temperatures but has the disadvantage of high density (the steel piston has about 178% more mass than the aluminum piston, resulting in a higher inertia of the engine (Table 3). On the other hand, the aluminum alloy EN AC-48000 has a high strength-to-weight ratio but has relatively low mechanical properties at high temperatures and under cyclic loads.

3. The stress parameters do not have much difference among them but the temperature parameters have a large difference. The FEM shows that by changing the position of the pin hole up with 5 mm, the pressure resistance parameters (200 Pa) increase (+7.6% for steel and + 8.5% for Al alloy). At 300 Pa the pressure resistance parameters increase also (+7.7 for steel and +8.5 for Al alloy) by changing the position of the pin hole up with 5 mm. This is clearly highlighted in Figs. 14-a and 14-b (linear growth). From the point of view of thermal stress (Von Mises) the change of pin position from 25 mm to 30 mm (Table 3) translates to a small decrease 1.34% for steel and -1.7%for Al alloy) of thermal stress (Von Mises).

4. The applied pressure can crack the piston at certain points, especially above the pin. The thermal stress of the piston has an opposite effect and leads to a reduction in stresses on the inside of the pin hole, but on the other hand the pressure exerted over the pin hole moves towards the inside of the pin hole. Also, the maximum temperature of the steel piston reduces the amount of air entering in the combustion chamber, reducing the volumetric efficiency.

5. To satisfy all the requirements with regard to successful application of pistons, in particular high temperature, mechanical loading, reduce weight and fuel consumption there are several concepts available that can be used to improve its use, such as design, materials, processing technologies, etc.

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