Design of automobile piston group

Ziao Yang [a], Jiakun Zou [b] and Jingcheng Cai [c]

Shandong University of science and technology, Qingdao 266590, China

[a]yzashao@qq.com, [b]455480392@qq.com, [c]1213409528@qq.com

Abstract

The paper takes the related parameters of the Jetta EA113 gasoline engine as a reference, detailed structural design for piston, piston pin, piston pin and piston ring and check the strength and stiffness of the structure, ensuring that the designed piston group has high reliability and durability.

Keywords

The design of the piston group, Working conditions, Reliability, Durability.

1. Introduction

Piston groups, including piston, piston pin and piston ring, are the parts of reciprocating movement in the cylinder, which are the hardest working conditions in the engine. The working reliability and durability of the engine are to a great extent related to the working conditions of the piston group.

2. Working conditions and design requirements for the piston group

2.1 Working conditions of the piston

(1) The mechanical load of the piston

In the engine work, the mechanical load of the piston consists of the periodic gas pressure, the reciprocating inertia force, and the resulting lateral forces. Under the action of mechanical load, the different stresses in each part of the piston: The top of the piston is dynamically bending stress, and the piston pin bears the tension and bending stress, and the ring bank bears the bending and shear stress. In addition, there is greater wear in the ring and skirt. In order to adapt to the mechanical load, the design of piston requires proper wall thickness and reasonable shape. That is, under the premise of ensuring enough strength and rigidity, the structure should be as simple and light as possible, and the transition at the section should be smooth, so as to reduce the stress concentration.

(2) The heat load of the piston

When the piston works in the cylinder, the top surface of the piston bears the effect of transient high temperature gas, and the maximum temperature of the gas is up to $2000°C \sim 2500°C$. So the temperature of the piston top is also high. Piston not only has high temperature but also uneven temperature distribution, so there is a great temperature gradient between every point, which is the root of thermal stress. It is these thermal stresses that play an important role in cracking on the top surface of piston.

(3)The strong wear and tear

The lateral force generated by the engine is larger than that of the piston. Meanwhile, the high-speed reciprocating motion of the piston in the cylinder will cause strong wear between the piston group and the cylinder surface. Because of the poor lubrication conditions, the wear condition is quite serious.

2.1.2 Design requirements for the piston group

(1) Choosing materials with good thermal strength, wear resistance, small specific gravity, small thermal expansion coefficient, good thermal conductivity, good grinding and technological properties.

(2)There is a reasonable shape and wall thickness. Good heat dissipation, strength, stiffness meet the requirements, as far as possible to reduce weight, to avoid stress concentration;

(3)Ensuring that the air tightness of the combustor is good, the gas channeling and oil channeling are less and the friction loss of the piston group is not increased.

(4)The best fit of piston and cylinder sleeve can be maintained under different working conditions.

(5)Reduce the heat absorbed by the piston from the gas, and the heat absorbed by the piston can be removed smoothly.

(6) Under the condition of low oil consumption, sufficient lubricating oil is ensured on the sliding surface.

2.2 The material of the piston

According to the requirements of the piston design mentioned above, the piston material should meet the following requirements:

(1) High heat intensity. That is, there is still enough mechanical properties at high temperature to $300 \sim 400°C$ make the parts not damaged.

(2) Good thermal conductivity and poor heat absorption. To reduce the temperature in the top and ring areas and to reduce the thermal stress.

(3)The coefficient of expansion is small. The gap between the piston and the cylinder can be kept in a small gap.

(4) Small proportion. In order to reduce the reciprocating inertia force of the piston group, the mechanical load and balance weight of the crankshaft linkages are reduced.

(5) Good wear reduction performance (less friction coefficient between cylinder liner materials), wear resistance and corrosion resistance;

(6) Good technological and low cost.

In the engine, gray cast iron has been widely used as piston material because of its good wear resistance, corrosion resistance, small expansion coefficient, high thermal strength, low cost and good manufacturability. But in recent decades, due to the improvement of engine speed and the continuous improvement of working process, gray cast iron piston is gradually eliminated by the two basic shortcomings of the major and poor thermal conductivity, which are gradually eliminated by aluminum based light alloy piston.

The advantages and disadvantages of aluminum alloy are the opposite of grey cast iron. The proportion of aluminum alloy is small, and it occupies about 1/3 of gray iron. The weight of the structure is only $50 \sim 70\%$ the piston of cast iron. Therefore, its inertia is small, which is of great significance to the high speed engine. Another prominent advantage of aluminum alloy is that it has good thermal conductivity, and its heat conduction coefficient is about twice as high as cast iron, which makes the piston temperature drop significantly. For the gasoline engine, the use of aluminum piston also creates important conditions for improving the compression ratio and improving the performance of the engine.

Eutectic Al Si alloy is the most widely used piston material at home and abroad. It can be cast, and can be forged. The hypoeutectic Al Si alloy with silicon content of about 9% has a slightly larger thermal expansion coefficient, but because of its good casting performance, it is suitable for mass production process and has wide application.

Comprehensive analysis, the piston of the engine is made of aluminum silicon alloy.

3. The design of the piston group

3.1 The design of the piston head

3.1.1. Main points of design

The piston head includes the piston top and the ring part. Its main function is to bear the air pressure, and pass it to the connecting rod through the pin seat, and at the same time cooperate with the piston ring to cooperate with the cylinder to seal the working fluid. Therefore, the main points of the design of the piston head are:

(1) Ensure that it has enough mechanical strength and stiffness to avoid cracking and excessive deformation, because the excessive deformation of ring groove will affect the normal operation of piston ring.

(2) Ensure that the temperature is not too high, the temperature difference is small, prevent excessive thermal deformation and thermal stress, create favorable conditions for the normal operation of the piston ring, and avoid the thermal fatigue cracking at the top.

(3) The size is as compact as possible, because the general compression height H_1 is shortened by 1 unit. The whole engine height can shorten $1.5 \sim 2$ units and significantly reduce the piston weight. And H_1 is directly affected by the size of the head.

3.1.2. Determination of the height of compression

The selection of the piston compression height will directly affect the total height of the engine, as well as the size and quality of the cylinder liner and the body. Reducing the piston compression height as much as possible is an important principle for the design of the modern engine piston. The compression height H_1 is made up of the height of the firepower h_1, the height of the ring with the h_2, and the size of the upper skirt h_3.That is

$$H_1 = h_1 + h_2 + h_3$$

In order to reduce the compression height, the height of the ring bank, the ring groove and the diameter of the pin hole should be compressed on the basis of the guaranteed strength.

(1) The position of the first ring

When the piston ring is arranged to determine the compression height of the piston, the position of the first ring must be determined first, that is, the height of the so-called fire shore h_1. To reduce H_1, Of course, I want h_1 to be as small as possible. But h_1 too small will cause the first ring temperature to be too high, causing the piston ring elastic relaxation, bonding and other failures. Therefore, the selection principle of fire shore height is that as far as possible to meet the requirements of the thermal load of the first ring groove, as much as possible. Commonly gasoline engine $h_1 = (0.06 \sim 0.12)D$, D is the piston diameter, The standard diameter of the piston of the engine $D = 80.985mm$, determining that the height of the fire bank is as follows:

$$h_1 = 0.09D = 0.09 \times 80.985 = 7.289mm$$

(2)The height of the belt

In order to reduce piston height, piston ring groove axial height b should be as small as possible, so that the piston ring inertia force is also small, it will reduce the impact on the side of ring groove, and help to improve the durability of ring groove. But if b is too small, making the ring process will be difficult. In a small and high speed internal combustion engine, the general gas ring is high $b = 1.5 \sim 2.5mm$, and the oil ring is high $b = 2 \sim 5mm$.

The engine uses three piston rings, and the first and second rings are called the compression ring (gas ring), and the third ring is called the oil ring. Take $b_1 = 1.5mm$, $b_2 = 1.75mm$, $b_3 = 3mm$

The height of the ring bank is c, and it should be ensured that it will not be damaged under the load caused by gas pressure. Of course, the second ring shore load is much smaller than the first ring, and the temperature is low. It can be destroyed only when the first ring has been destroyed. Therefore, the height of the ring bank is generally the largest and the other is smaller. The statistics of the actual engine show that $c_1 = (0.04 \sim 0.05)D$, $c_2 = (1 \sim 2)b_1$, The gasoline engine is close to the lower limit.

$$c_1 = 0.045D = 3.64mm.$$

$$c_2 = 1.5b_1 = 1.5 \times 2 = 3mm$$

Therefore, the height of the ring

$$h_2 = b_1 + c_1 + b_2 + c_2 + b_3 = 1.5 + 3.64 + 1.75 + 3 + 3 = 12.89mm$$

(3) Upper skirt size

After determining the arrangement of the piston head ring, the compression height H1 is finally determined by the distance h1 from the piston pin axis to the lowest ring groove (oil ring groove). In order to ensure that the oil ring works well, the axial gap in the ring is very small, and the ring groove will be stuck and failure if there is a large deformation. So in the general design, selection of the piston skirt size should make the pin seat above the oil ring groove is positioned above the pin diameter, and ensure the strength of pin seat will not be weakened by the slot, but also not due to pin seat material distribution caused by uneven deformation, the impact of oil ring.

To sum up, the compression height of the piston can be determined H_1, for the gasoline engine $H_1 = (0.35 \sim 0.6)D$

$$H_1 = 0.4 \times D = 0.4 \times 80.985 = 32.394mm$$

$$h_3 = H_1 - h_1 - h_2 = 32.394 - 7.289 - 12.89 = 12.761mm$$

3.1.3 Piston top and belt section

The shape of the piston top depends mainly on the selection and design of the combustor. From the angle of piston design, in order to reduce the heat load and stress concentration of piston group, we hope to adopt the shape of the piston top with the smallest heating area and the simplest processing, namely the flat top. Most gasoline engines are using a flat top piston, because the EA113 5V 1.6L engine is a high compression ratio $\varepsilon = 9.3$. Therefore, a piston similar to a flat top is used. The actual statistics show that the minimum thickness of the top of the piston is, gasoline engine $\delta = (0.06 \sim 0.1)D$, that is $\delta = (0.074 \times 80.985) = 5.993mm$. The heat received by the piston top is mainly passed through the piston ring. Special experiments show that for the unforced cooling piston, the heat transferred to the cylinder wall by piston ring accounts for 70 to 80%, and the piston to the cylinder wall accounts for 10 to 20%, while the air to the crankcase and oil only account for about 10%. Therefore, the thickness of the piston δ top should be increased gradually from the center to the periphery, and the transition fillet r should be large enough, so that the heat absorbed by the piston top can be smoothly guided to second and three rings, so as to reduce the heat load of the first ring and reduce the maximum temperature.

The piston head should be fitted with a piston ring, and the side wall must be thickened. Generally take $r = (0.05 \sim 0.1)D$, taking 0.074 D as 5.993mm. In order to reduce carbon accumulation and heat, the top surface of the piston should be smooth and even polished in some cases. The complex shape of the piston top should be paid special attention to avoid the sharp angle. All the sharp corners should be carefully trimming so as not to melt at high temperature.

(2) The section of the ring

The girdle section, in order to ensure the high heat load, the piston has enough wall thickness of the piston δ', so that the heat conduction is good, and the heat is not concentrated too much in the highest ring. The average value is $\delta' = (1.5 \sim 2.0)t'$. It is very important for the reliability and durability of the ring and ring grooves to design the cross section of the ring groove and the matching gap between the ring and the ring groove. The corner of the bottom of the trough is generally 0.2~0.5mm. Piston ring bank sharp edges must be chamfered, or when the shore part and the cylinder wall pressing burrs, it may get stuck piston rings, cause serious leakage and become overheated, but too big and chamfer of the piston ring leakage increase. Generally, the chamfering is $(0.2 \sim 0.5) \times 45^\circ$.

(3) Ring and ring grooves

Design of ring and ring groove of the bank should maintain the normal work of the piston and the piston ring, reduce oil consumption, prevent the piston ring sticking stuck and abnormal wear, the gas ring groove under the plane should be vertical with the axis of the piston, and the bottom of the barrel to ensure contact ring work, to reduce possibility of channeling oil. The backlash in the damage of piston ring case as small as possible, at present, the first ring and ring groove clearance is generally 0.05~0.1mm, two, three appropriate small, 0.03~0.07mm, oil ring is smaller, which is conducive to the stability of piston ring and reduce oil consumption, must be determined with backlash the oil return hole of oil ring groove, and uniformly arranged main thrust surface side of the oil return hole has important significance to reduce oil consumption, the three word gap and gap of piston ring as shown in table 1:

Table 1. opening gap and backlash of piston ring

Piston ring	Opening gap / mm	Backlash / mm
First ring	0.20 ~ 0.40	0.05 ~ 0.09
Second channel ring	0.20 ~ 0.40	0.03 ~ 0.06
Third channel ring	0.25 ~ 0.45	0.03 ~ 0.06

The backlash of the piston ring is Δ'' large, so as to avoid interference between the ring and the corner of the bottom of the groove. The general gas ring is Δ'' =0.5 millimeter, and the Δ'' of the oil ring is larger, as shown in Figure 1.

(4) The strength checking of the ring bank

At the beginning of the expansion stroke, the first piston ring is tightly pressed on the first ring under the explosion pressure. Due to the throttling effect, the first ring bank above the pressure p_1 below the pressure is much greater than p_2, the unbalanced force will produce large bending and shear stress in the shore root, when the value exceeds Aluminum Alloy in its working temperature limit strength or fatigue limit stress, shore root may rupture, show special the test, when the piston acting on the maximum pressure of $p_{\max}$, $p_1 \approx 0.9 p_{\max}$, $p_2 \approx 0.2 p_{\max}$, as shown in figure 3.2.

Known $p_{\max} = 4.5MPa$, so $p_1 \approx 0.9 \times 4.5 = 4.05MPa$, $p_2 \approx 0.2 \times 4.5 = 0.9MPa$

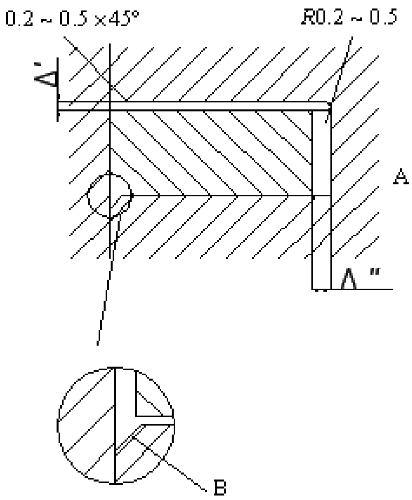

Fig. 1 the gap between the ring and the ring groove and the structure of the ring groove

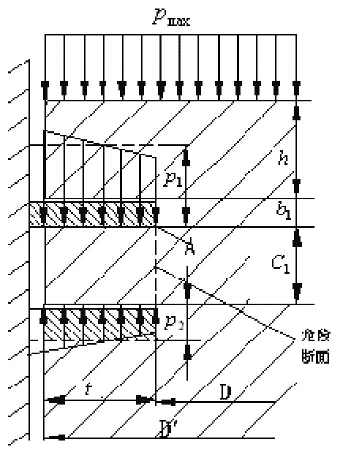

Fig. 2 the force of the first ring on the bank

The circular shore is a circular plate with a thickness of c_1 and the diameter of the inner and outer circle of D and D'. It is fixed along the inner cylinder. It is very complicated to calculate the stress of the fixed surface accurately, so it can be simplified to a simple cantilever beam for general calculation. Under the usual size ratio, the diameter of the trough bottom (An Gen) can be assumed to be $D' = 0.9D = 0.9 \times 80.985 = 72.89mm$, and the depth of the ring groove is t':

$t' = 0.05D = 0.05 \times 80.985 = 4.05mm$

So the bending moment that acts on the root of the shore is:

$$(p_1 - p_2)\frac{\pi}{4}(D^2 - D'^2)\frac{t'}{2} = 0.0026 p_{\max} D^3 \tag{1}$$

The coefficient of bending section is approximately equal to that of the section of the ring bank.

$$\frac{1}{6}c_1^2 \pi \times 0.9D = 0.47 c_1^3 D$$

So the bending stress on the dangerous section of the ring bank root

$$\sigma = \frac{0.0026 p_{\max} D^3}{0.47 c_1^2 D} = 0.055 p_{\max} (\frac{D}{c_1})^2 \tag{2}$$

$$= 0.055 \times 4.5 \times (\frac{80.985}{3.64})^2 = 1.23 \quad N/cm^2$$

The shear stress of the same reason is as follows:

$$\tau = 0.37 p_{\max} \frac{D}{c_1} = 0.37 \times 4.5 \times \frac{80.985}{3.64} = 37.04 \quad N/cm^2 \tag{3}$$

The formula of joint stress is as follows:

$$\sigma_\Sigma = \sqrt{\sigma^2 + 3\tau^2} = \sqrt{1.23^2 + 3 \times 37.04^2} = 38.64 \quad N/mm^2 \tag{4}$$

The allowable stress of the aluminum alloy is in consideration of the decrease in the strength of the aluminum alloy at high temperature and the stress concentration at the root of the ring bank. $[\sigma] = 30 \sim 40 \ N/mm^2, \sigma_\Sigma < [\sigma]$, Check the qualification.

4. Conclusion

In the design process of the piston, respectively the main structure parameters of piston, piston pin, piston pin and piston ring, analyzes its working conditions, summarizes the design requirements, selection of appropriate materials, and were checked and related to the stiffness strength, which meets the actual requirements.

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