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NUMERICAL ANALYSIS OF VALVE STRUCTURE OF HIGH POWER MARINE ENGINE

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Professional paper

Summary

Valve as an important part of the gas distribution mechanism, is an crucial part of the engine. When the engine works, the valve is subjected to high temperature, high impact, frictional wear and corrosion and other harsh working conditions, and the reliable and durable valve has an important impact on the safety and reliability of the engine. In this paper, a model of four-stroke marine diesel engine valve is used as the research object, and the intake valve set and exhaust valve set models are established respectively. Heat transfer simulation and failure analysis of inlet and exhaust valves of different structures and materials under different operating conditions were carried out using finite element analysis. The results show that the different valve structures and manufacturing materials have different effects on the reliability of the valves; Changing the valve structures and choosing different valve manufacturing materials have a greater impact on the heat transfer and deformation, thus affecting the overall reliability of the valves.

Key words: *Marine Diesel Engine; Valve; Numerical Simulation; Numerical Analysis*

1. Introduction

The intake valve and exhaust valve are important components of internal combustion engines. They withstand the corrosion of high-temperature gas and the impact of explosion pressure in the cylinder. Reliable and durable valves have an important impact on the safety and reliability of internal combustion engines. Although the technical diagnosis of the engine can be carried out by controlling the direct parameters (pressure and temperature) of the engine, the optimization of engine parts is also necessary [1]. With the innovation of modern engine technology, the design of the engine tends to develop in the direction of high speed and high power enhancement. The resulting increase in the temperature of the combustion chamber and other corrosion threats, which also makes the intake and exhaust valve damage factors more and more. Therefore, more stringent requirements are put forward for the heat resistance, corrosion resistance and wear resistance of the valve. At present, the world's research on the reliability of engine intake and exhaust valves mainly focuses on the following three aspects[2-4]: (1) Engine intake and exhaust valve failure mechanism, (2) Intake and exhaust valve friction and wear characteristics, (3) Materials for casting valves.

This paper investigates the influence of valve structure on valve reliability. According to the valve’s structure, there are three main forms of failure at the disc end face[5-8]: valve head fracture, aluminium deposition and high-temperature deformation; at the disc part, there is mainly ablation and detachment; at the disc cone face, there is wear, corrosion and burnout; at the neck part, there is mainly corrosion, cracks, perforation and fracture; at the rod part, there is mainly failure due to wear; at the locking clip groove, there is mainly impact fracture and fatigue fracture; at the rod end face, there is less failure. It can be seen that the causes of valve failure are complex and diverse, and structural failure is one of the fundamental causes of valve failure.

Due to being in a high temperature and high frequency shock operating environment, the valves are subjected to continuous impact of combustion load, shock load, and temperature load under different operating conditions, and the valves are subjected to fatigue damage, which leads to failure. With the development of computer technology, the study of valve reliability using computer software has become more and more extensive [9-10]. The engine valve, valve seat and valve guide assembly contact models were established based on finite element analysis software. The stress pattern of the valve under different operating conditions is analyzed, and the stress, strain and deformation diagrams of vonmises can be obtained. Scholars from various countries [11-17] used finite element analysis software to simulate the temperature and stress fields of valves under different operating conditions, which provided a theoretical basis for failure analysis of valves and optimal design of valves. In addition, the valve materials in industrial manufacturing are still mainly austenitic heat-resistant steel and martensitic steel. However, nickel-based high-temperature alloys have high strength and hardness, good corrosion resistance, oxidation resistance and anti-scuffing properties. In meeting the mechanical properties, physical properties and corrosion resistance requirements of ultra-high load diesel engine valves, nickel-based high-temperature alloys have advantages. Therefore, nickel-based high-temperature alloys have become one of the hot spots of current research.

In this paper, based on the existing research results, a systematic and in-depth study is carried out for a model of four-stroke marine diesel engine valve. Through thermal structure analysis, the working environment of the valve is simulated, and the temperature distribution, deformation and stress distribution of the intake and exhaust valves are determined. Combined with the problems arising in the actual production and operation process, the influencing factors of valve failure and their laws are explored in depth to provide a reliable calculation basis for valve design optimization.

2. Models and Parameters

In order to analyze the effect of valve structure changes and material differences on valve reliability, a valve set model is established (Fig.1 illustrates its structure). The valve structure and material are shown in Table 1, and the materials properties of valves are shown in Table 2. Compare the two structures of intake valve a and b: both are consistent material, but structure-a into the valve head part has a weld layer, structure-b into the valve head part without weld layer; compare the two structures of exhaust valve A and B: structure-A is consistent material, and exhaust valve and exhaust valve seat have weld layer, structure-B for the valve rod and valve head part of two materials, valve head part without weld layer, valve seat still has weld layer.

(a) intake valve (b) exhaust valve

Fig.1 Different valve structures

Table 1 Various structures and materials of valves

	Intake valve		Exhaust valve	
	a	b	A	B
Valve	Consistent material ; With weld layer 40Cr10Si2Mo	Consistent material ; Without weld layer NiCr20TiAl	Consistent material ; With weld layer 50Cr21Mn9Ni4 Nb2WN	Valve stem and head sections are friction-welded together. Valve stem：40Cr10Si2Mo Valve head：NiCr20TiAl
Valve Seat	40Cr10Si2Mo			
Catheter	High phosphorus cast iron			
Locking Clip	10#Steel			

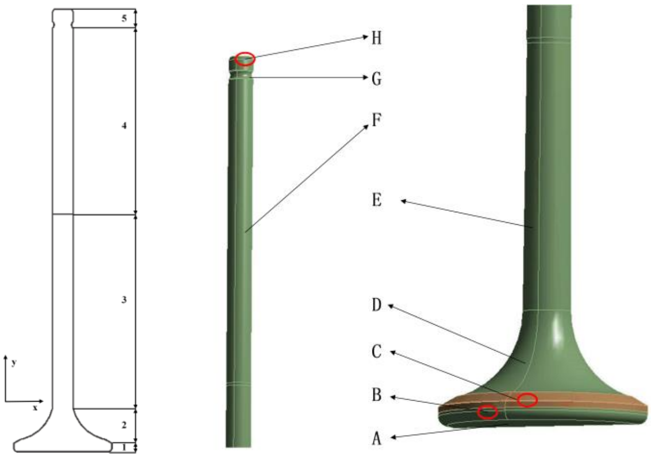
Table 2 materials properties of valves

	50Cr21Mn9Ni4Nb2WN	40Cr10Si2Mo	NiCr20TiAl	Stearic VI steel
thermal expansion coefficient(/℃)	1.61E-05	1.14E-05	1.37E-05	1.36E-05

3. Boundary Conditions

3.1 Temperature field boundary conditions

The heat transfer within the intake valves differs from the exhaust valves due to the different boundary conditions around each valve. The valves were properly divided in order to better evaluate the actual influence around the valves. Assuming that the valve is heated in a homogeneous state, divide the valve into several parts by using the idea of finite element method, and then the boundary conditions of each part are defined separately, as shown in Fig.2.Theoretically, after valve partitioning, each zone corresponds to a different temperature value and heat transfer coefficient. Each region has a different value depending on its location in turn, Assign values according to the heat transfer coefficient empirical formula. Exhaust valve as an example, The heat transfer coefficients and temperature boundary conditions at different locations (Fig.2) are given in Table 3. The heat transfer coefficient and wall temperature of each section were evaluated [18-19] and custom tuned by combining literature references and experience.



（a） （b）

Fig.2 Boundary condition definition partition

Table 3 Temperature and heat transfer coefficient of each part

Position	A	B	C	D	E	F	G	H
Temp.(/℃)	1100	800	300	Change in X-direction	400	200	200	200
Heat transfer coefficient (/w/m2·k)	523	700	3605	Change in X-direction	400	200	200	200

3.2 Preload force

Under different operating conditions, the fit of the valve set has a great influence on the load, and the temperature distribution and stress distribution of the valve and related parts are also different as a result. According to the free length of the spring, the assembly length and the spring stiffness in the closed state, using the formula (1), the spring preload force can be obtained as 1100N.

$$F = k \triangle x \quad (1)$$

F is Elasticity(N), k is Coefficient of stiffness， $\triangle x$ is Spring stretch length（mm）。

3.3 Cylinder peak pressure

At the cylinder peak pressure condition, and the cylinder peak pressure acts directly on the bottom surface of the valve head. According to the measured cylinder pressure data, the maximum cylinder peak pressure of exhaust valve is 20Mpa.

3.4 Constraint

Set the model forces in the FEA software : Set the direction of its own gravity downward ; The valve seat is installed in the fixed hole slot, and the fixed constraint is applied at its upper surface, (constraint x, y, z,and 6 degrees of freedom of x, y, z rotation, valve rod axis direction is y direction); Valve catheter is installed in the fixed position of the piston and cannot be moved, so the displacement of the outer cylindrical surface of the valve guide in x, y and z directions is constrained, and the displacement is set to 0; Valve seat can only have displacement in y direction, and the displacement on its upper surface in x and z directions is constrained, so the displacement on the constrained surface is set to 0.

4. Grid accuracy analysis

The 1/2 exhaust valve model is the research object, different mesh sizes are set (as shown in Fig.3), and the mesh quality is changed to analyze the effect of mesh accuracy on the temperature field and deformation of the valve. The model is unstructured meshed using the mesh module that comes with ANSYS software. Among them, the adaptive mesh model has 98,939 mesh nodes and 48,387 cells. The mesh model with a defined body sizing of 3 mm has 147,574 mesh nodes and 78744 cells. The mesh model has 209,947 mesh nodes and 101,610 cells. Comparing the temperature field and deformation of valve head part when different grid sizes are set (as shown in Fig.4), it can be seen that the influence of grid quality on valve temperature value, temperature distribution, deformation distribution and deformation size is smaller. Therefore, a faster adaptive mesh is used to simulate the temperature and stress fields of the valve.

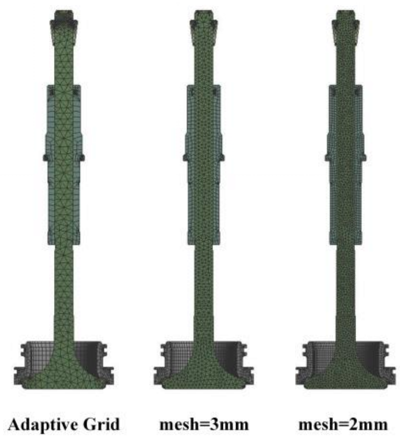
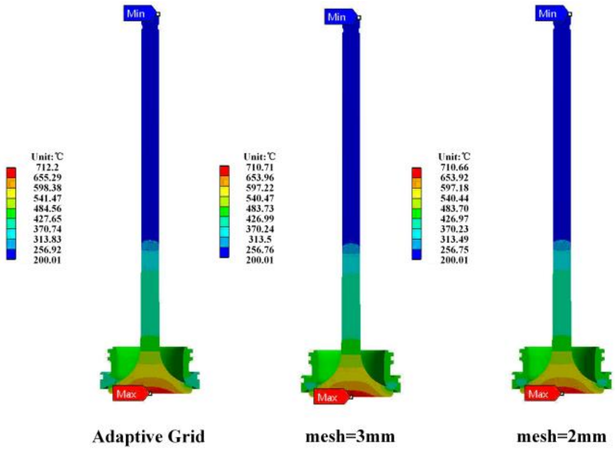
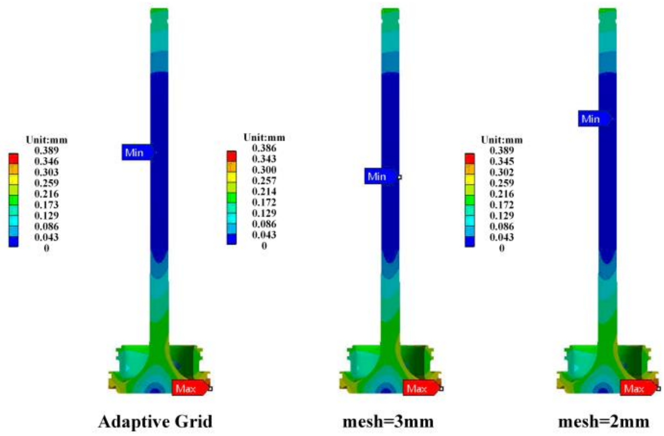


Fig.3 Model mesh comparison



（a） Temperature field distribution



（b） Deformation distribution

Fig.4 Comparison of simulation results with different meshes

5. Discussion of numerical simulation results

5.1 Comparison and analysis of temperature field results

5.1.1 Intake valve

Fig.5 shows the temperature distribution of intake valves with different structures. The results show that the temperature distribution gradient of two groups of one material is the same, and the distribution area of the highest temperature is basically the same. However, the temperature distribution at the valve with and without the weld layer has some differences. Since the head of structure-a has a weld layer and the head of structure-b does not have, the heat transfer of the valve in structure a has an extra layer, which is transferred from the material 40Cr10Si2Mo to the Stearic VI steel, and the thermal conductivity of these two materials is different. And about structure-b intake valve, there is no temperature transfer between different materials and the heat conduction is more smooth. Therefore, the change in structure and material leads to a decrease in the maximum value of temperature at the head of the structure-b intake valve.

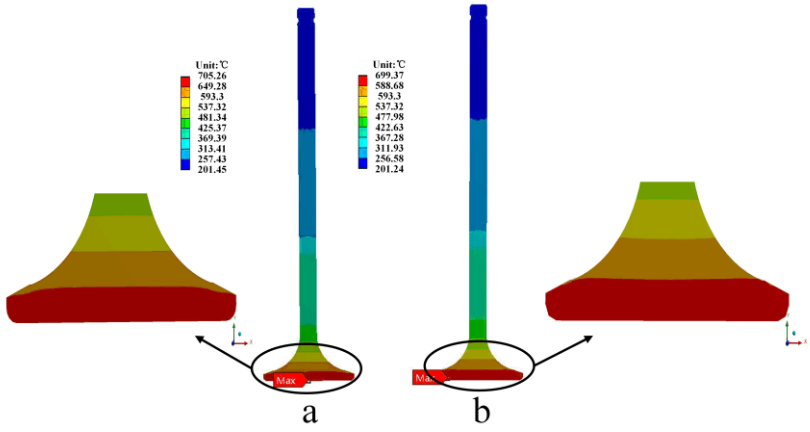


Fig.5 Comparison of intake valve temperatures of different structures

5.1.2 Exhaust valve

Fig.6 shows the comparison of the temperature of valve head section for two different structures. The change in structure causes a change in the heat transfer between the valve head section and the valve seat. In the closed condition, the change of the valve structure causes the heat transfer between the valve head and valve seat to change, resulting in different temperature distribution gradients at the contact area between the valve head and valve seat. Compared with the temperature values in the contact part of the valve seat and valve head section in the structure-A, the boundaries in the structure-B are more obvious and the changes in the temperature values are small.

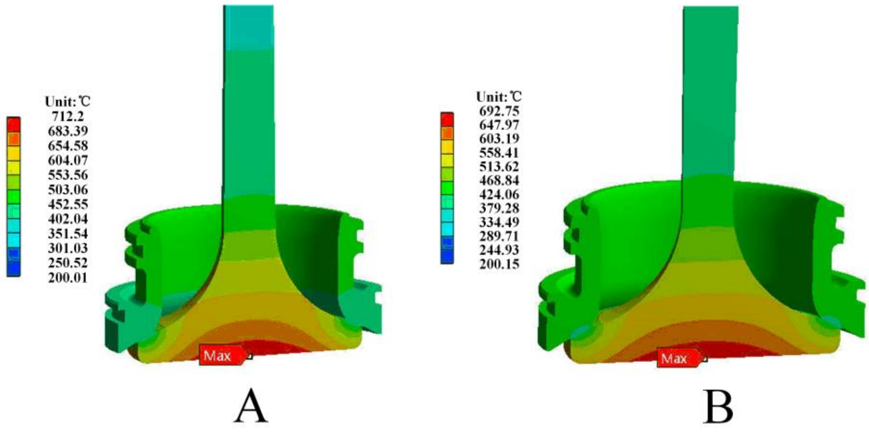


Fig.6 Comparison of exhaust valve temperatures of different structures

Fig. 7 and Fig. 8 show the temperature distribution of the contact edge line between the overlay layer and the valve seat for valves of different structures. From the temperature values of the overlay layer and the gradient of temperature distribution, it can be seen that the valve overlay layer in structure-A does not have a positive effect on the temperature transfer, but affects the efficiency of heat transfer, thus leading to a different temperature distribution of the valve. Comparing the temperature distribution of the valve seat overlay layer under the two structures, it can be seen that the temperature transfer efficiency of the valve in structure-B is higher and the cooling effect is better.

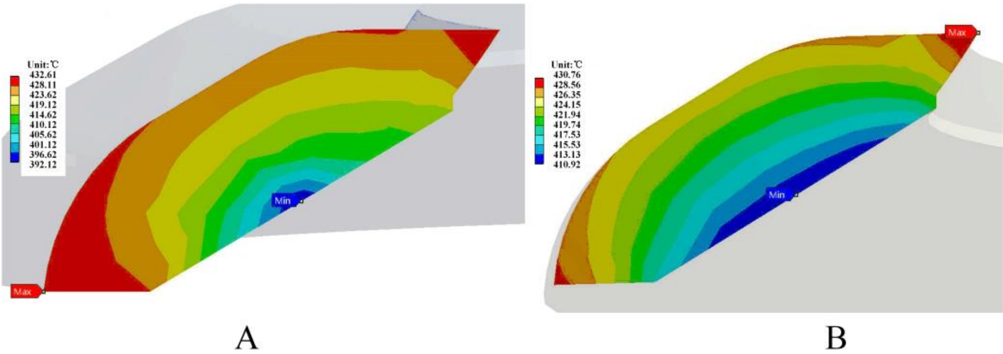


Fig.7 Temperature distribution of valve seat overlay layer of different structures

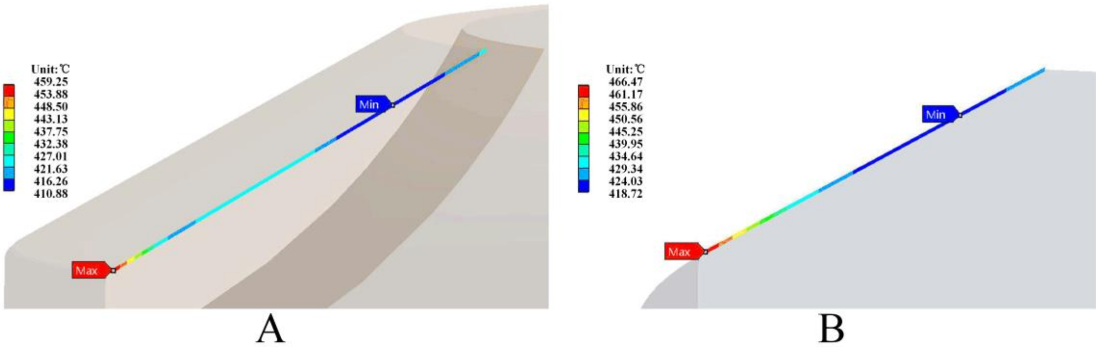


Fig.8 Temperature distribution of valve edge line of different structures

5.2 Comparison and analysis of heat engine coupling calculations

5.2.1 Intake valve

Fig.9 shows the comparison graph of the deformation of intake valves of different structures. The results show that the maximum deformation of two intake valves of one material are located in the same region, but the gradient of the deformation distribution of the two structures differs greatly. From the valves material properties can be seen (as shown in Table 2), there is a difference between the thermal expansion coefficient of the valve material in structure-a and the thermal expansion coefficient of the overlay layer (Stearic VI steel), which makes the deformation of structure-a larger than that produced by structure-b in the corresponding position. According to the local distribution diagram in the figure, it can be seen that the distribution gradient of the valve deformation of structure-a is also larger than that of structure-b.

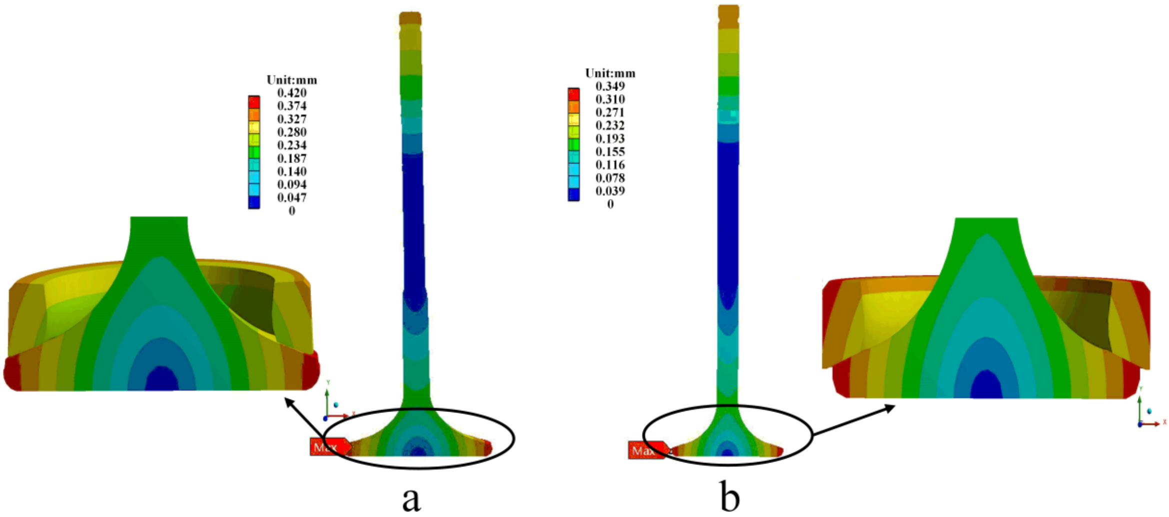


Fig.9 Comparison of intake valve deformation of different structures

Fig.10 shows the distribution of the equivalent stress of the intake valve under the coupling condition of the heat engine. Comparing the maximum equivalent stress of the intake valves of the two structures, it can be obtained that the maximum equivalent stress value is lower when there is no weld layer on the valve head. Structure-a and b intake valves produce the same location of the maximum equivalent stress, and the same as gradient of distribution. Therefore, the change of valve structure has a small effect on the equivalent stress, while the change of material will make the equivalent stress of the two structures different.

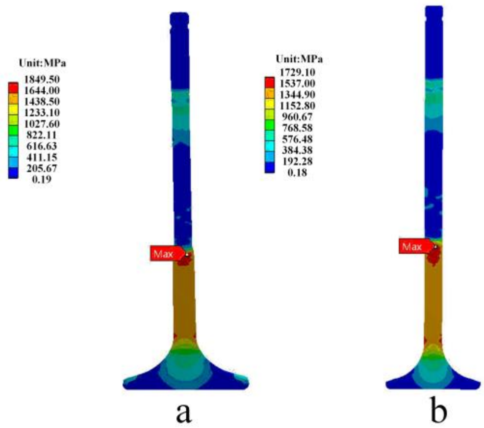


Fig.10 Comparison of the equivalent stress of intake valves of different structures

5.2.2 Exhaust valve

Fig.11 shows the comparison graph of deformation of exhaust valves of different structures.The results showed that the deformation of the two sets of valves with one material used for the through-body and those welded by two materials differed significantly. The deformation distribution of valves and valve seats of two materials is more regular in structure-B.The maximum deformation of the valves in the two structures are in the same position, but the maximum deformation of the valves in the structure-B is much smaller than that in the structure-A. Compared with the valve material in the structure-A, from the valves material properties can be seen (as shown in Table 2), the thermal expansion coefficient of the valve material in the structure-B is closer to that of the overlay layer (Stearic VI steel). It can be seen that the gradient of the deformation of the valve head, weld layer and valve seat in the structure-B is more regular.

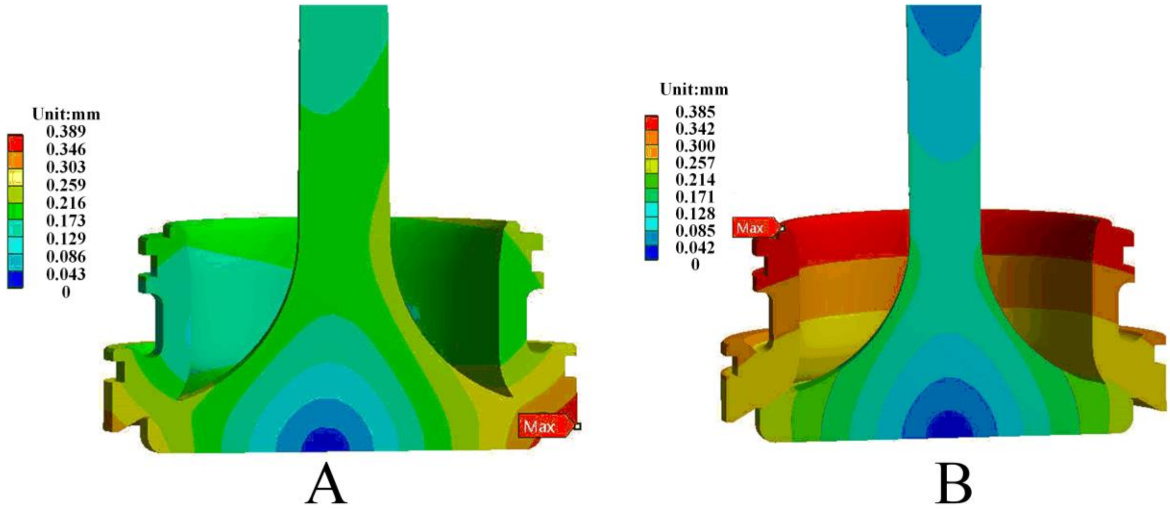


Fig.11 Comparison of deformation of exhaust valves of different structures

Fig.12 shows the equivalent stress distribution of the exhaust valve under the hot-engine coupling condition.The simulation results show that the maximum equivalent stress value of the exhaust valve of structure-B is lower compared to that of structure-A. The locations of the maximum equivalent stress generated by the structures-A and B are very different, and the gradients of the distribution of the exhaust valve heads are also different. The simulation results show that the stresses at the weld layer of the head part of structure-A change faster and the distribution is irregular. The stress mutation is the location where more failure problems occur, which easily leads to failure behaviors such as head fracture and disc cone surface wear. The maximum equivalent stress appears at the rod section, and the stress variation gradient is large near this location, which easily leads to the failure behavior of rod fracture. According to the calculation results of structure B valve, it can be seen that the stress at the connection between the valve head part and the rod part is the largest, the stress at the center of the valve disc surface is the smallest, and a small dramatic change in stress occurs at the connection between the rod part and the head part. Therefore, this joint in the structure-B is the most prone to failure problems, which can cause the whole head to fall off in severe cases.The structure-B is designed in such a way that the stresses decrease continuously upward along the rod section. Due to the impact of the valve seat on the head part, the equivalent stress and the exhaust valve deformation tend to change differently. In structure-A and structure-B, the equivalent stress is highest at the overlay layer (contact with the valve seat) and then decreases to the sides. Therefore, the change of exhaust valve structure and the change of material have a great influence on the equivalent stress, which not only makes the equivalent stress distribution of the two structures different, but also changes the location of the maximum equivalent stress.

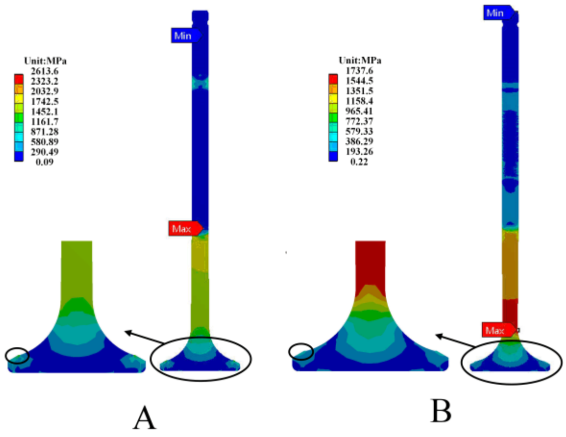


Fig.12 Comparison of the equivalent stress of exhaust valves of different structures

6. Conclusions

（1）Valve overlay layers do not have a positive effect on temperature transfer, but rather affect the efficiency of heat transfer. Due to the difference in the coefficient of thermal expansion of the material, additional thermal stresses are added, which increases the amount of thermal deformation and thus affects the reliability of the valve.

（2）The change in intake valve structure has less effect on the equivalent stress in the closed condition. The improvement of the mechanical properties of the material makes the equivalent stress of structure B intake valve lower. The change of the exhaust valve structure and the change of the material have a great influence on the equivalent stress, and the deformation of the exhaust valve head part of structure B is smaller. Different deformation distributions indicate different deformation rates, which affect the distribution of the equivalent stress and the location of the maximum equivalent stress, which in turn affects the reliability of the valve.

（3）In summary, the structure and material changes on the intake and exhaust valve temperature distribution, thermal deformation and equivalent stress distribution have different degrees of influence. The change of valve structure has a greater effect on the temperature distribution, while the change of material has a greater effect on the thermal deformation.

In the later study of valve failure influencing factors and reliability, the author will simulate the valve operating environment under closed and open condition, design relevant tests to obtain relevant data, in order to quantify the laws between structural and material changes on the temperature and stress changes in the valve head.

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