THE INFLUENCE OF WELDING FLASH ON ENHANCING HEAT TRANSFER OF STEEL PISTON

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In order to study the influence of welding flash on heat transfer performance of steel piston cooling gallery, the pistons with different structures are studied. In this paper, the finite element simulation calculation of the steel piston with the welding flash and the non-flash structure on the same model and the annular cavity section is carried out separately, and the amount of carbon deposited in the top of the steel piston and cooling gallery after 1000 hours test is measured. The comparative analysis finds that the existence of welding flash hinders the heat transfer of cooling gallery, resulting in an increase in the temperature of the inner surface of cooling gallery, which in turn increases the temperature of entire piston head. Carbon deposits in the top surface and cooling gallery of the steel piston, which affects the cooling effect.

Key words*: steel piston, cooling gallery, welding flash, carbon deposit*

1. Introduction

In order to meet the requirements of high-performance diesel engine reinforcement and emissions, the load on engine components is increasing. During the working process of engine, the piston needs to withstand higher burst pressure and high temperature load. The cooling gallery is a very efficient heat transfer enhancement method, which can effectively deal with the serious thermal load problem of the engine piston[1-3]. Steel pistons with cooling gallery are widely being used in commercial automotive engines.

At present, most forged steel pistons are formed by friction welding to connect the piston head to the skirt[4-5]. A closed cooling gallery is formed between the head and the skirt of the forged steel piston. Compared with the aluminum alloy piston, the cooling gallery inside the forged steel piston has a large cross-section and an irregular shape. Friction welding is a solid-state connection technology. The welding parameters required for welding are less, the control accuracy and reliability are high, and the welding parameters are easy to monitor[6]. However, the base metal does not melt during the friction welding process, which is a solid phase thermocompression bonding, the joint is a forged structure, the metal grains in the welding zone are refined, the structure is dense, and the inclusions are dispersed. Therefore, the welding flash is generated in the cooling gallery due to the welding gap[7], and its structure is shown in Fig.1.

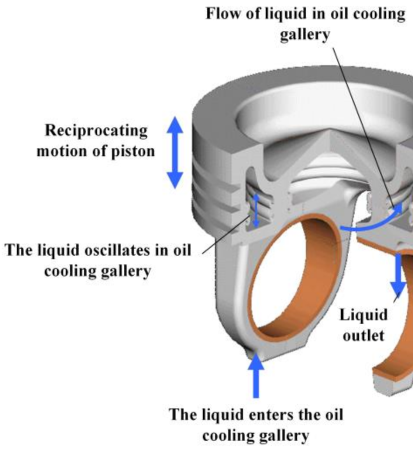


Fig. 1. The Schematic diagram of steel piston with welding flash

The flow in the cooling gallery becomes more complicated due to the welding flash and variable cross-section on the annular cavity. When the oil is injected into the inlet of the cooling gallery, there is still a certain speed when it reaches the top of the cooling gallery. Therefore, a vortex appears at the inlet of the annular cavity, and then the oil flow tends to be stable[8-10]. The liquid flow passes through the welding flash and variable cross-section, and is suddenly changed direction, affecting the flushing of the liquid relative to the wall surface, thereby affecting the heat transfer effect.

Many scholars have done a lot of experiments and simulations about cooling gallery of aluminium alloy piston. Such as Wu-Shung Fu[11]simplified the three-dimensional cooling gallery into a "Π" shaped and two-dimensional channel, which was transformed into a dynamic boundary problem, where the finite element method and Lagrangian dynamics method were employed to study the oscillation frequency, amplitude and the Reynolds number on the heat transfer rate of the piston cooling. Jinfeng Pan and Roberto Nigro[12]studied the oscillation characteristics of the cooling gallery in both two-dimensional and three-dimensional models and simulated the heat transfer of the cooling gallery during the whole injection process at different crank angles, obtaining the distribution and filling rate of the oil with respect to crank angle which provides the foundation for further study on the effect of the filling rate on the heat transfer coefficient. Wang Peng[13-14]simplified the model, taking piston cooling gallery as the research object, and used the high-speed camera to capture the flow pattern when the crank angle varied. The effects of oscillation frequency, gas content and two-phase distribution on the turbulent flow characteristics and heat transfer mechanism were discussed. Deng Xiwen[15]investigated the factors of the heat transfer performance, the instantaneous oil distributions, the relative oil velocity, the instantaneous acceleration and the velocity of the piston, and so on.

At present, some scholars have studied the enhancement mechanism of multi-cavity oscillation cooling of various types of diesel engine pistons based on the orthogonal analysis method, considering the influence of structural parameters and filling rate[16]. These studies revealed the effects of axial and circumferential heat transfer [17] under the influence of factors such as geometry [18], structural parameters [19], oscillation frequency [20], cooling medium [21], and piston space angle [22]. In this paper, a model of piston is taken as the research object, by comparing the heat transfer effect of cooling gallery with large welding flash and no welding flash, and the structural strength of the combustion chamber. Calculate and analyze the influence of welding flash on the thermal load and reliability of the forged steel piston.

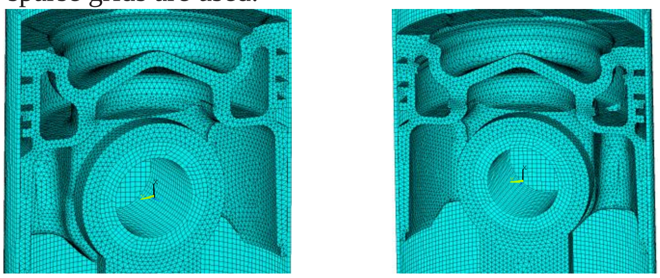
2. Parameters and Models

As the internal combustion engine works, the piston is also influenced by gas pressure from the cylinder. Therefore, the connect rod and piston pin should be both considered into the modeling. The piston used for the present investigation in the finite element analysis adopts steel material, the material properties are described in Table 1. In addition, the operation process of the internal combustion engine can be regarded as a stable working condition, so the temperature field distribution of the piston can be treated as a steady-state temperature field.

Table 1. Material characteristics of a steel piston

Density (kg/m3)	Young’s modulus (GPa)	Poisson’s ratio	Thermal conductivity(w/m·K)	
7800	209	0.28	Average of the four zones of the combustion chamber	800
			Top land	1600
			First ring groove	26000
			Pin hole	3600

Considering the symmetry of piston, the 1/2 model of piston, piston pin and the small end of connect rod is the finite element analysis model. Determine initial temperature and material properties, ensure good contact between the connecting rod and pin, pin and pin bore, and the liner and skirt. In addition, the cylinder liner and symmetric plane are properly restrained and loads are applied to the top, ring groove and piston land. A steel piston model with welding flash and without is shown in Fig.2. The piston models are unstructured meshed using the meshing technology that comes with ANSYS. In order to show the datas variation law and the effective comparison calculation results, the two models adopt a uniform grid size. In areas where the temperature gradient is large or the local characteristic surface of the piston is small, dense grids are used, and in areas where the temperature gradient is small, relatively sparse grids are used.



a) The structure without welding flash   b) The structure with welding flash

Fig. 2. The mesh model of steel piston with different structures.

The cycle time of diesel engine is very short. When the diesel engine enters the normal operation state, the temperature of piston surface tends to be constant. Only the area 2mm away from the piston surface has obvious fluctuation, and the temperature of other parts remains unchanged. Therefore, in the calculation, it is only assumed that the piston is a steady temperature field in the whole working process. According to the results of hardness plug experiment and experiences[23]], the boundary conditions of the key position of forged steel piston are determined. The values for the key positions are shown in **Table 1**. It can be seen from the results in Table 2 that the absolute error between the calculated value and the experimental value is less than 5%, and the calculation accuracy meets the requirements of engineering application. Moreover, the temperature change of piston is not obvious under different grids. Therefore, the influence of grid size on temperature can be ignored.

Table 2. Comparison of hardness plug test results and finite element key position results

Grid size （mm）	combustion bowl rim （℃）	combustion bowl center （℃）	Top land （℃）
1	439.25	350.87	324.87
2	439.34	348.21	323.96
3	438.96	348.19	323.25
Experiment value	445	351	325

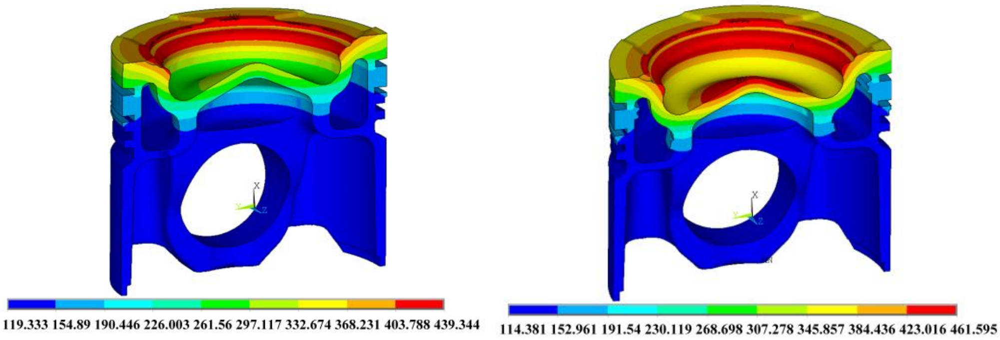
3. Finite Element Analysis and Discussion

The structure and size of the cooling gallery have certain influences on the structural strength. The volume ratio affects the retention period of oil in cooling gallery, and the cooling effect is also affected, which in turn affects the structural reliability. The welding flash not only affects the structure of the cooling gallery, but also changes the volume ratio. Therefore, it has a great influence on the flow of the cooling oil in the cooling gallery. The welding flash is one of the main factors affecting the cooling effect.

3.1. The Influence of Welding Flash

3.1.1 Temperature field comparison

In order to compare the influence of welding flash on the heat transfer effect and structural strength, a type of piston is taken as the research object. The hardness plug temperature measurement experiment of steel piston under the rated working condition is used as the boundary condition for the temperature field simulation calculation. Considering the factors such as temperature, burst pressure, and inertial force, the thermal-mechanical coupling calculation is per-formed to obtain the deformation and stress of the key position of the piston. The temperature field results are shown in Fig.3, and the unit of temperature in the fig.3 is °C.



(a) The structure without welding flash (b) The structure with welding flash

Fig. 3.Temperature field of steel piston.

By comparing the temperatures of the combustion bowl rim and the cooling gallery surface, the welding flash has a great influence on the cooling effect. The welding flash reduces the heat exchange efficiency, resulting in an increase in the surface temperature of the cooling gallery, which increases the risk of carbon deposition in the cooling gallery. Carbon deposition can be assessed by measuring the thickness of the carbon in the top of the piston and the cooling gallery after prolonged operation.

3.1.2 the comparison of hoop stress

During the working process of piston, the combustion chamber is mainly subjected to two forces, namely mechanical stress and thermal stress. These two forces cause cracks in different parts of the piston combustion chamber. Because of the gas pressure, the piston will bend with the pin as the fulcrum. At this time, a large tensile stress is generated at the combustion rim along the pin axis, which is a mechanical stress. As shown in fig.4, by comparing the influence of welding flash on the structural strength, it is found that the stress distribution trends of the two structures are consistent. The mechanical stress of the steel piston with welding flash structure is larger, and the damage to the strength of the piston is also greater. In addition, the mechanical stress at the bottom and the throat of combustion chamber are high. Due to the combined effects of thermal load, burst pressure, and inertial force, the temperature of the piston combustion chamber with welding flash is higher, the amount of deformation increases, and the mechanical stress becomes larger.

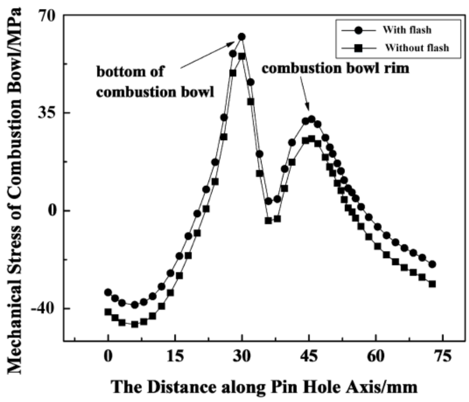


Fig. 4. Mechanical stress of combustion bowl along pin hole axis.

Fig.5 shows the thermal stress of combustion chamber along thrust axis. When the load is large, the piston temperature is high, and thermal expansion occurs at the combustion rim. The compressive stress is formed here due to the constraint. The results show that, the welding flash piston has a larger compressive stress at the combustion rim, and it is easy to form cracks at the edge of combustion rim, compared with the piston without welding flash. This is because the piston with the welding flash has a large temperature gradient and a large amount of thermal deformation, so the ability to withstand load is reduced.

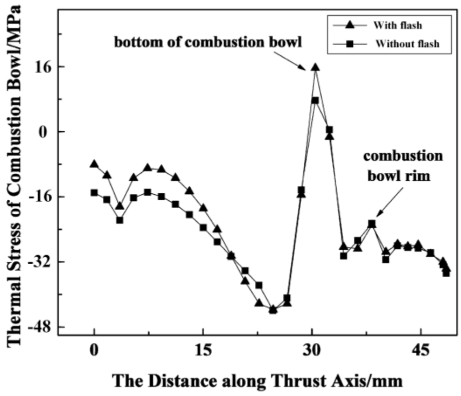
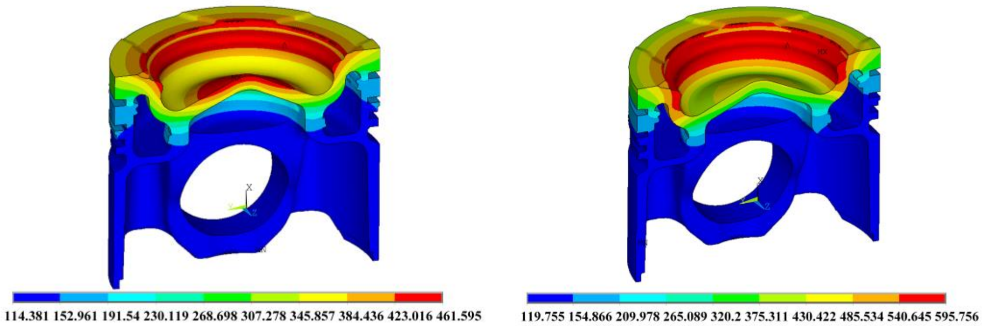


Fig. 5. Thermal stress of combustion bowl along thrust axis.

3.2. The Influence of Welding Flash Size

The effect of different flange sizes on the piston temperature is given in Fig.6, and the unit of temperature in the fig.6 is °C.. By comparing the temperatures of combustion rim and the cooling gallery surface, it can be seen that the size of welding flash has a great influence on the cooling effect. Obviously, the larger the welding flash size, the lower the heat exchange efficiency of cooling gallery. This leads to an increase in the temperature of cooling gallery inner surface, and it is to deposit carbon more easier, which in turn continues to affect the heat exchange efficiency.



（a）a small welding flash size （b）a large welding flash size

Fig.6 Temperature field of steel piston

4. Experiment Results and Discussion

After a long period of operation, due to high temperature corrosion, the top material will oxidize when it is overheated, so that its chemical composition changes, and finally an oxide layer is formed on the top surface of the piston. In severe cases, it will cause ablation of the top of the piston. The piston is subjected to a 1000 hours endurance test, and then the thickness of the oxide layer and the carbon deposit in the combustion and cooling gallery are measured and analyzed. The main technical parameters of the engine are shown in Table 3.

Table 3. The main technical parameters of the engine

Bore diameter(mm)	Stroke(mm)	Compression Ratio	Rated power(kW)	Rated engine speed(rpm)	Peak pressure(bar)
112	145	17.5	276	2100	230

Cut the piston after the experiment, then mark the positions where more carbon deposits occurred. Observe the surface morphology of carbon deposits, use the thickness gauge to measure the thickness of the combustion oxide layer and the carbon layer in the cooling channel at different positions. The measure positions are shown in fig. 7. As shown in Fig. 7, the main thrust side (TS) and the secondary thrust side (ATS) , the front side (FS) and the rear side (RS) of piston were marked.

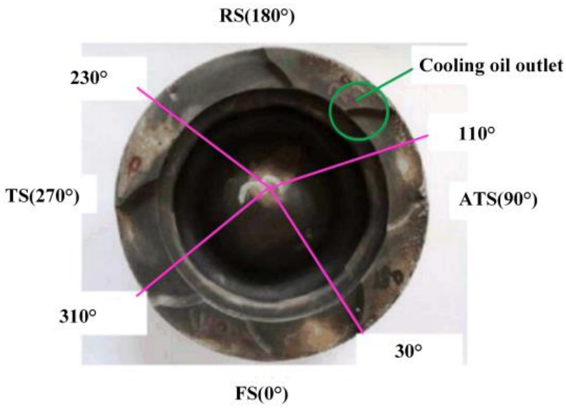


Fig. 7. The measure position of steel piston

The thickness of oxide layer in the combustion is shown in Table 4. By comparing the thickness of the oxide layer at different positions, it can be seen that the welding edge affects the flow of cooling oil in the cooling channel, which reduces the cooling effect on the outlet side, resulting in an oxide layer in the combustion chamber. During the reciprocating motion, the maximum thicknesses of the oxide layer are different at the cutting position and cross-section (shown in Fig. 7) due to the change of fluid flow structure. During the reciprocating motion, each cylinder is at a different crank angle position at the same time, so are the thickness of oxide layer on the same section. However, it is been found that, the maximum thickness of the oxide layer produced by each cylinder is very close at the same position. In addition, the largest thickness of the oxide layer generated at the bottom of the combustion chamber at the 30° section, which can be seen from Table 4.

Table 4. The thickness of oxide layer (μm)

Positions	Cylinder number	Section of 30°	Section of 110°	Section of 230°	Section of 310°
The transition point between the bottom of valve crater and combustion	1#	9.23	7.98	4.86	8.1
	3#	7.07	7.92	8.9	6.91
Combustion rim	1#	8.28	8.41	7.34	7.71
	3#	5.52	9.73	9.74	8.04
Combustion bowl	1#	5.43	6.93	4.94	3
	3#	11.9	6.72	7.92	7.9

The thickness of carbon deposit in the cooling gallery is shown in Table 5. Comparing the thickness of carbon deposits at different sections, the carbon deposit thickness on the inlet side is smaller than that at the outlet. The welding flash edge affects the flow of the cooling oil in cooling gallery, reduces the heat transfer efficiency of the cooling gallery in the outlet side, and increases the thickness of the carbon deposit on the outlet side. The data in Table 5 further illustrate that the welding flash causes the heat transfer efficiency to decrease, resulting in increasing the surface temperature of the inner surface of cooling gallery, and the risk of carbon deposition is greatly increased, resulting in carbon deposition in the ring bank.

Table 5. The thickness of carbon deposit in cooling gallery (μm)

Position	Cylinder number	Section of 30°	Section of 110°	Section of 230°	Section of 310°
Top of cooling gallery	1#	60.9	88.9	77.8	60.5
	3#	66.7	74.1	65.4	67.4

5. Conclusions

The following conclusions can be drawn from the comparison of numerical simulation and experimental results.

⑴ The welding flash edge changes the ideal design structure of the cooling gallery. It affects the flow of cooling oil, reduces the heat transfer efficiency, causes the temperature of the inner surface of cooling gallery to rise, generates carbon deposit, and reduces the reliability of piston.

⑵ Compared with the piston without welding flash, the piston with welding flash has no change in the stress distribution trend of the combustion. But the tensile stress and compressive stress are increased to different extents, which reduce the reliability of piston.

⑶ The oxide layer and carbon deposit in the welding flash piston are detected. It is found that the temperature of the combustion and the cooling gallery of the welding flash piston increased, resulting in an oxide layer on the top sur-face and carbon deposition in the cooling gallery. It is still not possible to quantify the effects of weld flashing changes, and it is necessary to further measure the amount of carbon deposited in the top of the piston and cooling gallery after running for a long time in the engine.

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