DESIGN AND FINITE ELEMENT ANALYSIS OF ENGINE VALVE SPRING

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The experimental results show that there is a fracture risk of the intake and exhaust valve spring during use, so it is necessary to study the performance of this spring. Compared with the original, the intake and exhaust valves respectively increase the number of spring turns while maintaining the same length, which improves the service life safety factor of the spring. The finite element statics analysis shows that the stress and strain of the valve spring are in accordance with the material required yield strength of 55SiCr. The finite element modal analysis shows that the low-order natural frequency of the valve spring differs greatly from the operating frequency of the valve, so there is no resonance problem. The fatigue life analysis results show that the service life of the valve spring meets the requirements of the China national standard GB/T 19055-2024 "Automobile Engine Reliability Test Method". The research results can provide technical support and reference value for the design of the engine valve spring.

Keywords: Valve spring; finite element analysis; Static analysis; modal analysis; Fatigue life analysis

1. Introduction

Cylindrical helical springs are critical components in diesel engine intake and exhaust valve systems. Due to the substantial impact loads exerted during engine operation, rigorous quality control must be implemented in the design, material selection, heat treatment, and assembly processes of these valve springs. Improper installation, inadequate fatigue life design, or flawed heat treatment processes can lead to premature fracture or functional failure. Scholars worldwide have systematically investigated helical spring engineering. In terms of structural optimization, Feng Jinzhi [1], Taktak M [2], Ke J [3], Dong Shimin [4] and many scholars[5, 6] have established comprehensive analytical models for spring geometry optimization. In terms of material properties, Qin Zongli [7], Li Dong

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[8], Hu Peng [9] et. al. studied the fracture form of valve spring and the material heat treatment process, etc. Sun Shen [10] studied the influence of rare earth elements Ce/Nb and other added to the valve spring steel properties, and summarized the unqualified fracture forms and fracture causes of valve spring steel materials. In terms of valve spring assembly, relevant technical standards also specify the technical indicators of valve spring installation. Therefore, the valve spring failure analysis has a relatively perfect design technology [11, 12].

However, the failure of the valve spring still exists, and the failure of the valve spring is often not caused by a single factor. Systematic design of valve spring and finite element simulation analysis are still effective methods for current valve spring design [13].

2. Case study and spring finite element modelling

2.1 Case Study

Entrusted by the enterprise, a brand-specific engine durability test rig was constructed, as shown in Fig. 1. During the accelerated testing process, a motor-driven camshaft actuation system cyclically operated the intake/exhaust valves. After approximately 803 hours of continuous operation, a critical failure mode was observed - the valve spring exhibited fatigue fracture, as shown in Fig. 2. According to the requirements of GB/T 19055-2024"Automobile Engine Reliability Test Method"[14], the test results do not meet the requirements of the national standard, so it is necessary to analyze the cause of valve spring fracture and redesign the spring structure.

1. Oil pool temperature meter 2. Oil pressure meter 3. Pressure reducing valve 4. Camshaft motor

5.Oil filter 6. Oil pump 7. Oil pump motor 8. Oil pool

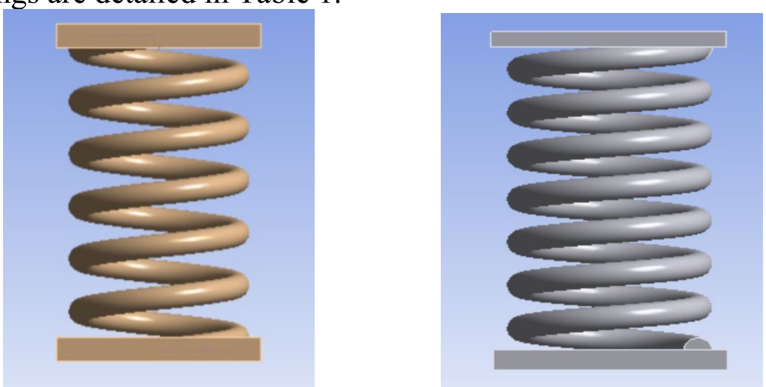
Fig. 1. Valve spring test bench

Fig. 2. Broken exhaust valve spring

Check the valve spring material parameters, the valve spring material is 55CrSi, which is a commonly used valve spring steel. In order to enhance the performance of this spring, the surface of the spring steel wire is polished and coated with oil, and the surface shot peening treatment increases the fatigue life and hardness. The heat treatment process of oil quenching and tempering is adopted, which meets the conventional heat treatment conditions. The fracture form is clearly the crack expansion caused by brittle fracture, so it is not considered to be a problem of material and heat treatment process, and it is necessary to re-design the spring structure.

2.2 Spring finite element modeling

Based on the provided design parameters and analytical formulas, a 3D parametric model of the intake/exhaust valve springs was developed, as shown in Fig. 3 below. Compared with the original design spring structure, the number of turns of valve springs is increased on the original basis while maintaining the same length. The exhaust valve spring operates in a harsh environment, so it should be 1 turn more than the intake valve spring in the design process to obtain a higher safety factor. Key geometric and mechanical parameters of the optimized helical springs are detailed in Table 1.



Intake valve spring assembly model Exhaust valve spring assembly model

Fig. 3. Assembly model of intake (left) and exhaust (right) springs

Table 1

Valve spring parameters

Name	Intake valve spring	Exhaust valve spring
Spring wire diameter /mm	3.0	3.0
Spring Outer diameter /mm	23.0	23.0
Spring middle diameter /mm	20.0	20.0
Spring inside diameter /mm	17.0	17.0
Total number of turns	7	8
Effective number of turns	5	6
Free length /mm	40.0	40.0
Preload force /N	120	180
Preload length /mm	31.3	29.1
Maximum design load /N	250	360
Length under maximum design load /mm	24.4	20.4
Direction of rotation	Right	Left

3 Finite element analysis of cylindrical helical springs

3.1 Grid division of valve springs

The valve spring model was meshed. In the process of discretization, considering that the part contains small features, such as small rounded corners and chamfers, the number of nodes and elements was increased during discretization, resulting in a decrease in solving efficiency. In order to effectively suppress the geometric features, the size of the suppressed features was set to 0.1mm. The mesh size of intake valve and exhaust valve spring was set to 1mm, and the meshed model after discretization is shown in Fig. 4. The FEA model statistics indicate the intake valve spring contains 76,193 nodes and 44,156 elements. The FEA model statistics indicate the exhaust valve spring contains 97,475 nodes and 59,282 elements. During the finite element simulation, the intake valve spring operating temperature was set to 300 ℃ and the exhaust valve spring operating temperature was 800℃ [15,16].

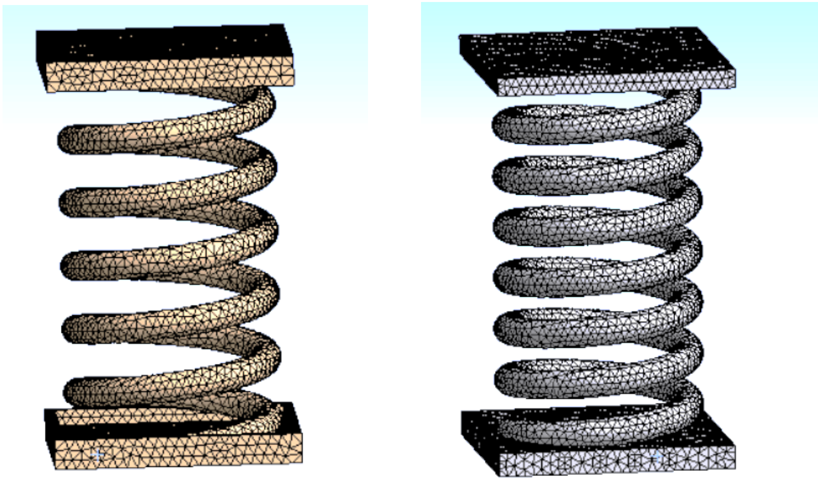


Fig. 4. Finite element mesh model

Among them, the material 55CrSi properties of the spring are shown in the Table 2.

Table 2

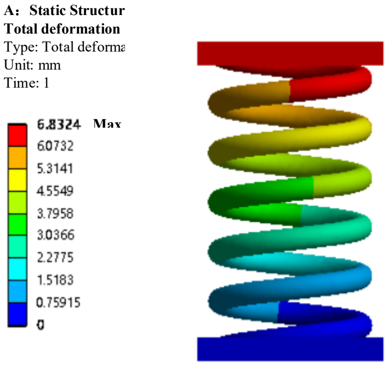
Material parameters of 55SiCr

Material property parameter	Values
Density / （kg/m³）	7730
Modulus of elasticity /GPa	206
Tensile strength /MPa	1814
Yield strength /MPa	1960
Poisson's ratio	0.3

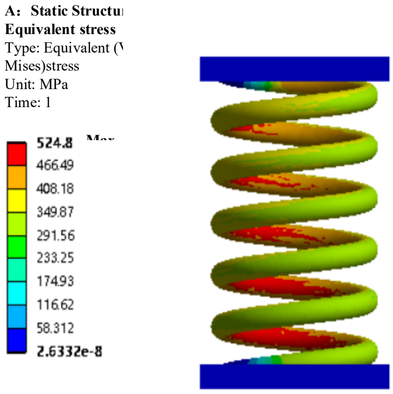
3.2 Static analysis of spring

The spring seat is fixed to the spring, the lower end of the spring is fixed on the simplified base, the upper end of the spring is loaded, and the nonlinear finite element solution process is carried out. For the intake valve spring, as can be obtained from table 1, the maximum load is 250N and the preload is 120N. For the exhaust valve spring, the maximum working load is 360N and the preload is 180N. The force states of inlet and exhaust valve springs are obtained respectively, as shown in Fig. 5.

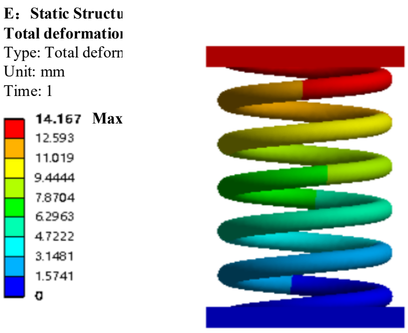
According to the deformation and stress nephogram of the intake valve spring in Fig. 5, the maximum stress of the intake valve spring under the initial tension is 524.8MPa.



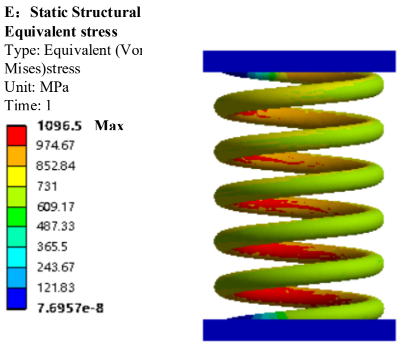
Preload deformation nephogram of intake valve spring



Preload stress nephogram of intake valve spring



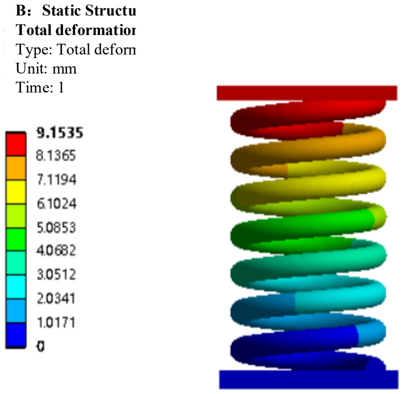
Deformation nephogram of intake valve spring under maximum load



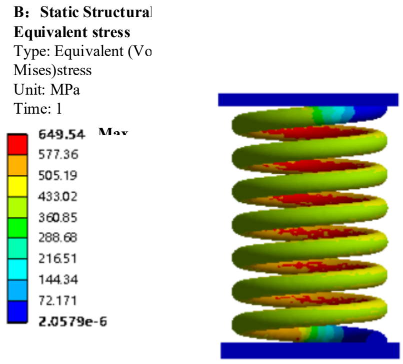
Stress nephogram of intake valve spring under maximum load

Fig. 5. Force diagram of intake valve spring

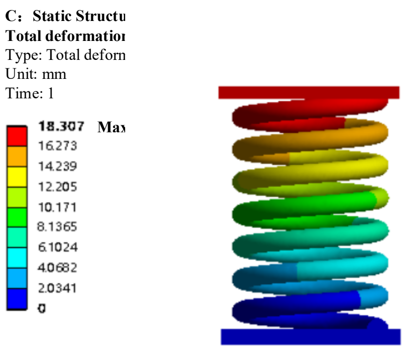
Under the maximum working load, the maximum stress is 1096.5MPa, and the value is less than the maximum ultimate strength of the spring material 1960MPa, and the safety factor at this time is N1=1960/1095.6=1.79. Thus, the static strength of the spring can be obtained. According to the deformation cloud map under preload, the maximum deformation under preload (120N) is 6.8mm, and the design deformation of the spring is 40-31.3=8.7mm, which is greater than this value. The maximum deformation of the intake valve spring under the maximum load is 14.2mm, and the design deformation of the spring 40-24.4=15.6mm is greater than the deformation. The deformation is within a reasonable range and will not have a substantial impact on the structure, indicating that the valve spring can produce enough elasticity when it reaches the design deformation, which meets the design requirements.



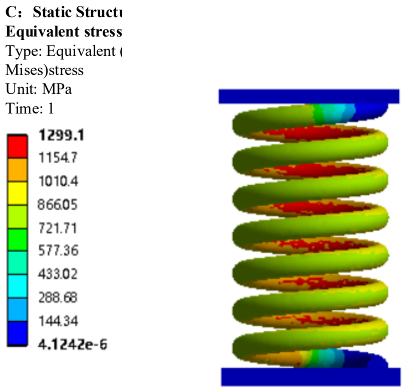
Preload deformation nephogram of exhaust valve spring



Preload stress nephogram of exhaust valve spring



Deformation nephogram of exhaust valve spring under maximum load



Stress nephogram of exhaust valve spring under maximum load

Fig. 6. Stress cloud diagram of exhaust valve spring

As can be seen from the deformation and stress cloud diagram of the exhaust valve spring in Fig. 6, the end deformation of the spring is small, and the middle deformation is large. When the initial tension is 180N, the maximum stress of the spring is 649.5MPa, and when the load is 360N, the maximum stress of the spring is 1299.1MPa. And the maximum stress of 1299.1MPa under the load is less than the maximum yield limit of 1960MPa of the spring material, and the safety factor is N2=1960/1299.1=1.5, so the static strength of the exhaust valve spring meets the requirements. According to the deformation cloud diagram under preload, the maximum deformation of exhaust valve spring under preload (180N) is 9.2mm, which is less than the design deformation of the spring 40-29.1=10.9mm. The maximum deformation of the exhaust spring under the maximum working load is 18.3mm, and the design deformation of the spring is 40-20.4=19.6mm, which is greater than the deformation, proving that when the deformation of the exhaust spring is equal to the design deformation, the valve spring can produce enough elasticity to meet the initial design requirements.

3.3 Modal analysis of valve spring

Under actual working conditions, the spring will be compressed and produce internal stress due to the initial tension during installation. These internal stresses cause the stiffness of the spring to increase, also known as "stress stiffening". Due to the presence of stress stiffening, the spring wire will become harder, so the natural frequency of the spring will also be affected. In this paper, the modal analysis of inlet and exhaust valve springs under prestress is carried out. Through the modal analysis of the spring, the 10-order vibration pattern of the spring is obtained as shown in Fig. 7.

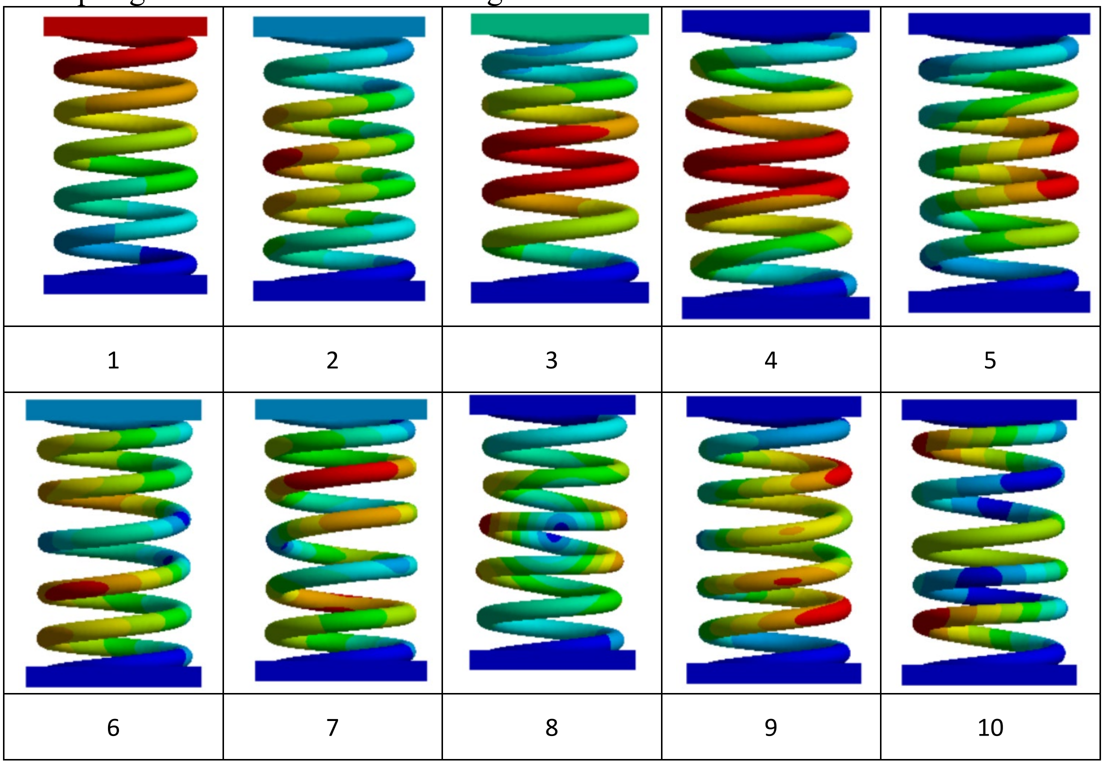


Fig. 7 The ten vibration modes of the intake valve spring at low frequency

Table 3

The intake valve spring pre-constrains the natural frequencies of each order

Modes order	Frequency /Hz	Modes order	Frequency /Hz
1	163.48	6	926.67
2	514.40	7	971.88
3	550.33	8	987.67
4	588.03	9	1084.5
5	603.37	10	1271.3

According to the analysis results, the third, fourth and sixth order vibrations are the transverse deformation of the spring. The first-order, second-order and fifth-order modes show axial deformation. The intake valve spring axial, torsional and transverse coupling deformation are the remaining four orders of vibration. According to Table 3, when the preloading force is 120N, the minimum natural frequency of the intake valve spring is 163.48Hz, and the operating frequency of the valve spring is 12Hz, which is far less than this value. Therefore, the intake valve spring will not have resonance in the actual working environment.

After the modal analysis of the exhaust valve spring under prestress, the 10-order modal mode figures are shown in Fig.8.

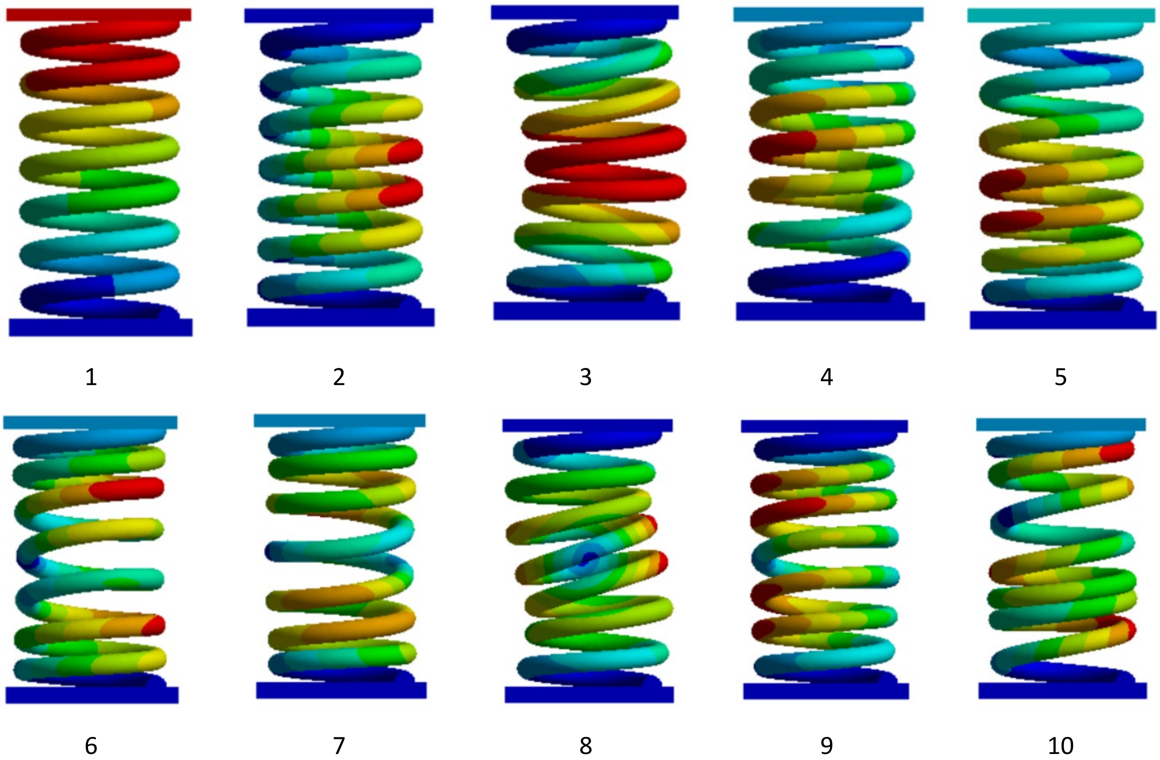


Fig. 8. The ten vibration modes of the exhaust valve spring at low frequency

Table 4

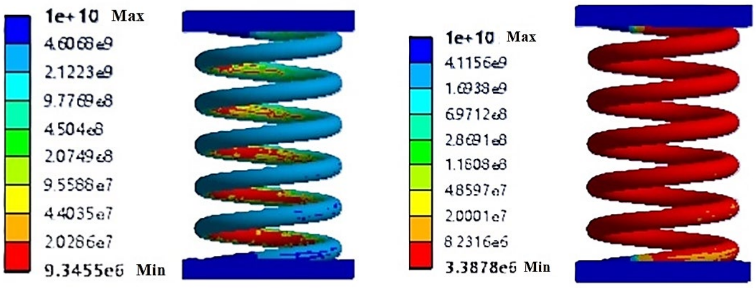
Exhaust valve springs pre-constrained natural frequencies of each order

Modes order	Frequency /Hz	Modes order	Frequency /Hz
1	153.41	6	870.16
2	469.44	7	905.11
3	496.53	8	928.79
4	508.10	9	993.64
5	512.57	10	1224.00

According to the analysis results, the third, fourth and sixth order vibrations show the transverse deformation of the spring. The first, second and fifth order vibrations show the axis deformation of the spring. The intake valve spring axial, torsional and transverse coupling deformation are the remaining four orders of vibration. As can be seen from Table 4, when the initial tension is 180N, the minimum natural frequency of the exhaust spring is 153.41Hz, and the operating frequency of the valve spring is 12Hz, which is far less than this value. Therefore, the exhaust spring will not have resonance in actual working conditions.

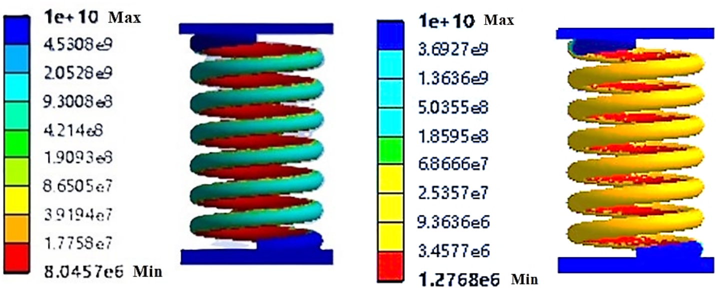
3.4 Fatigue life analysis of valve spring

Valve spring in the actual work will be affected by alternating load, a large number of valve spring failure studies found that the valve spring fatigue fracture is a common failure form, so it is necessary to analyze the valve spring fatigue life. During the analysis of the valve spring, the S-N curve of the fatigue life of the modified material was obtained by consulting the relevant data. The fatigue life results of the inlet and exhaust valve springs obtained by using the Goodman stress correction method are shown in the following Fig.9.



Nephogram of fatigue life of intake valve spring under preload

Nephogram of fatigue life of intake valve spring under maximum load



Nephogram of fatigue life of exhaust valve spring under preload

Nephogram of fatigue life of exhaust valve spring under maximum load

Fig. 9 Fatigue analysis cloud image of valve spring

Based on the above analysis results, it can be seen that the shortest life of intake valve spring under the maximum working load of 250N is 1e10 times, and the shortest life of exhaust valve spring under the maximum working load of 360N is 1.277e6 times, which meets the national design requirements of 5e5-1e6 times. Whether under the condition of preload or maximum load, the life of the outside part of the two valve springs is significantly longer than that of the inside part after the support ring is excluded. The minimum cycle life of the spring appears in the position of the inner ring of the spring, which indicates that the inner part of the spring is the area with the lowest fatigue strength. This is consistent with the actual situation that cracks and fractures may first occur in this part, which is consistent with the analysis results mentioned in the national standard GB/T 19055-2024 " Reliability test methods for motor vehicle engines ", thus verifying the correctness of the fatigue analysis.

4. Conclusions

(1) The dynamic performance of valve springs is a critical determinant of engine operational safety. Valve spring fracture analysis demands comprehensive engineering expertise, as failure mechanisms often arise from complex interactions between material properties, manufacturing processes, and dynamic loading conditions. Common root causes include suboptimal heat treatment protocols, improper assembly procedures, and geometric design deficiencies.

(2) Increasing the number of turns of the valve spring can increase the safety factor of the spring. Through finite element analysis, it is found that increasing the size of the valve spring can significantly improve the use effect of the spring, make the safety factor significantly increase, and provide a high safety margin during use.

(3) The finite element method is a limited method for analyzing the structure and resonance of the valve spring. The result of finite element method verifies the occurrence position of the fatigue life of the valve spring and the rationality of the result of finite element analysis.

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