International Journal of Mechatronics and Applied Mechanics
2025, Issue 22, Vol. II

FINITE ELEMENT ANALYSIS AND OPTIMIZATION OF FATIGUE LIFE FOR ENGINE EXHAUST VALVES: DIMENSIONAL AND MATERIAL PERSPECTIVES

Shugang Wang
Tangshan Vocational & Technical College, Tangshan, Hebei, China, 063300
Email: wangshugang@tsvtc.edu.cn

Abstract - Entrusted by an enterprise, fatigue life testing was conducted on the intake and exhaust mechanism of a new engine model. After 6,800 hours of engine operation, valve fracture was observed, and the analysis confirmed that the structural failure was caused by fatigue. In response, the dimensional parameters of the valve structure were modified, a three-dimensional model of the optimized exhaust valve was established, and finite element analysis was performed on it. The results indicated that the exhaust valve with optimized dimensions could meet the service requirements. Meanwhile, to further evaluate the service performance of exhaust valves made of different materials, a comparison of the mechanical properties of exhaust valves with various material compositions was carried out. The research findings demonstrated that the improved and optimized exhaust valves could all satisfy the practical application needs.

Keywords: Valve, Finite Element Analysis, Modal Analysis, Fatigue Test, Structural Optimization.

1. Introduction

With the advancement of engine power, the operating conditions of engine intake and exhaust valves have become increasingly severe. Exhaust valves, in particular, endure high temperatures, high pressures and alternating loads. Consequently, improving the fatigue life of valve structures has emerged as a key focus of current research. However, due to the constraints of valve operating conditions, the optimization methods for valve life vary. Relevant scholars have accumulated diverse experiences in this regard.

In the optimization of engine valves, the calculation of thermodynamic conditions for valve operation is crucial [1]. Nevertheless, difficulties exist in determining the thermal temperature and thermal stress of the engine valve operating environment. Therefore, more straightforward and effective methods are often required for valve structure optimization. It has been noted by some scholars that powder metallurgy technology plays a significant role in enhancing the fatigue life of valve guide rods. This is particularly true for the improvement of structural hardness and wear resistance [2-4].

A fracture issue of a marine exhaust valve was addressed by Yang Xinglin et al. [5]. A thermo-mechanical coupling model of the valve was established based on the finite element method. The service life of the valve was ensured by increasing the safety factor. Research on the material and structure of exhaust valves was conducted by Deng Lijun et al. [6]. It was found by them that modifying the exhaust valve structure can alter heat transfer efficiency. Specifically, under the working condition without the exhaust valve surfacing process, the operating temperature of the exhaust valve can be improved and stress can be reduced. Extensive experimental studies and comparative numerical simulations were carried out. Through these studies, it has been confirmed that the finite element method is an efficient and relatively accurate approach for optimizing exhaust valve structures [7-9].

2. Finite Element Modeling of the Exhaust Valve

Entrusted by an enterprise, a bench test was conducted on the valve train of a certain engine model. After 6,800 hours of rated power testing, a neck fracture was found in the exhaust valve of cylinder 3, as shown in Figure 1.

https://doi.org/10.17683/ijomam/issue22

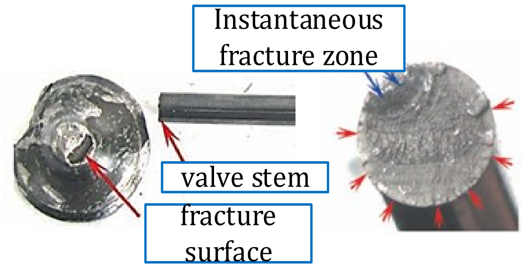

Figure 1: Morphology of the Fractured Exhaust Valve

The exhaust valve fractured at the neck arc position, and no bending was observed in the valve stem. Meanwhile, the piston top of this cylinder was punctured. The piston fractured at the piston pin hole, and the piston skirt cracked with pieces falling off. An analysis was carried out on the fracture morphology of the exhaust valve. Through this analysis, obvious fatigue fracture characteristics were presented in the structure [10-12]. Therefore, a study should be conducted on the fatigue life of the valve.

2.1 Exhaust Valve Model Parameters

Based on the structural parameters of the fractured valve, the structural parameters of the valve were optimized. The structural parameters of the valve before and after improvement are presented in Table 1.

Table 1 Structural Parameters of the Exhaust Valve

No.	Name	Symbol	Original Designed Size	Improved Size
1	Valve Stem Diameter	d	5.36 mm	6.36mm
2	Valve Head Diameter	D	53.34mm	53.34mm
3	Valve Overall Length	L	85.55mm	85.55mm
4	Valve Cone Angle	α	45°	45°
5	Valve Head Thickness	t	3.511mm	3.81mm
6	Valve Stem End Chamfer	C1	1.05mm×45°	1.25mm×45°
7	Valve Head Edge Chamfer	C2	0.5mm×45°	0.5mm×45°
8	Valve Head Edge Thickness	h	1.17mm	1.27mm

After the completion of 3D modeling, the finite element analysis was conducted on the exhaust valve performance using the original 4Cr10Si2Mo material. The performance parameters of this material are presented in Table 2.

Table 2 Mechanical Properties of the Material

Mechanical Parameters	4Cr10Si2Mo
Young's Modulus /GPa	206
Density/(kg/m^3)	7850
Tensile Strength/MPa	1980
Reduction of Area/%	≥35
Poisson's Ratio	0.3

2.2 Mesh Generation

The mesh generation was performed on the valve structure. A free meshing method was adopted in ABAQUS to generate the mesh. The valve structure with generated mesh is shown in Figure 2. The meshed results show that the structure consists of 4365 elements and 10476 nodes.

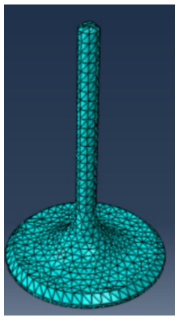

Figure 2: Valve Structure after Mesh Generation

2.3 Load Calculation

The external loads acting on the valve during operation are mainly from the drive of the valve spring and the effect of in-cylinder pressure. Two methods are available to obtain in-cylinder pressure: experimental measurement and thermodynamic calculation. In this study, the thermodynamic calculation method was selected to obtain the in-cylinder pressure at rated speed [13, 14]. The indicator diagram is shown in Figure 3.

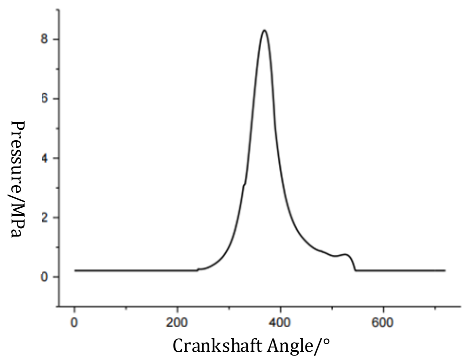

Figure 3: Indicator Diagram of In-Cylinder Combustion Pressure

During the calculation, the cylinder pressure curve was discretized. A relationship curve between cylinder pressure and time was obtained. The relationship table between cylinder pressure and time at rated speed is presented in Table 3.

Table 3 Relationship Table between Cylinder Pressure and Time at Rated Speed

Loading Time/s	Pressure/ MPa	Loading Time/s	Pressure/ MPa
0	0.2	0.085	2.05
0.06	0.2	0.09	1.18
0.065	1.02	0.095	0.87
0.07	3.11	0.096	0.8
0.075	7.81	0.097	0.2
0.0766	8.29	0.105	0.2
0.08	4.97	0.12	0.2

In this force calculation, the part constraint conditions of the valve were set as follows: the cam was set to rotate, and the valve and the upper spring seat were set to move axially. The lower spring seat, valve guide, and valve seat were all set to a fixed state. During the constraint setting, the camshaft was set to rotate at the rated speed. Fixed constraints were applied to the lower spring seat, valve guide, and valve seat. The cylinder pressure load was applied to the top of the valve stem.

3. Static Strength Analysis of the Valve

Taking the rated speed as an example, the in-cylinder pressure acting on the valve in the first stage was 0.2 MPa. In the second stage, the in-cylinder pressure on the valve was 3.11 MPa. In the third stage, the stress reached its peak at 8.29 MPa. Stress analysis was conducted using the in-cylinder pressures acting on the valve in these three stages. Then, the stress of the valve in the three stages and the deformation caused by the applied force were compared. Since this study mainly focuses on the fatigue life of the valve under extreme conditions, the maximum stress in the third stage was used as the main basis for analysis. This approach enables a better analysis of the stress on the valve and a more accurate calculation of its fatigue failure life.

Through the analysis of the static stress of the valve in the three stages, the stress distributions of the valve in the three stages were obtained, as shown in Figures 4–6.

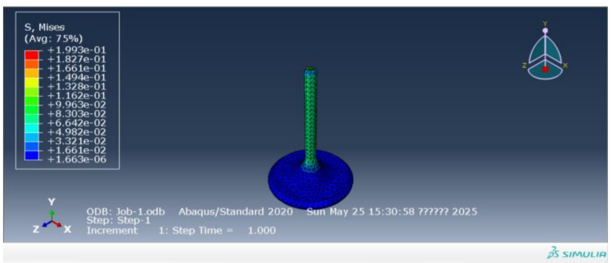

Figure 4: Stress Diagram of the Valve in the First Stage

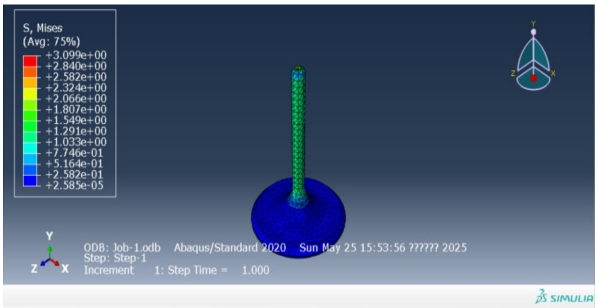

Figure 5: Stress Diagram of the Valve in the Second Stage

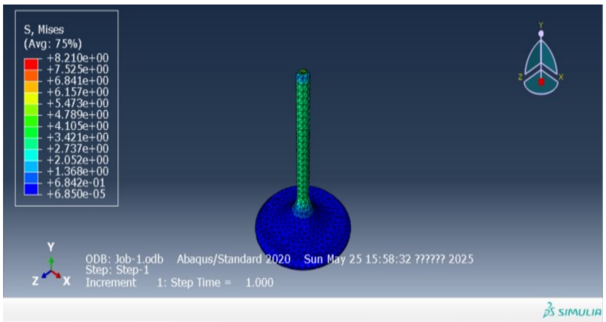

Figure 6: Stress Diagram of the Valve in the Third Stage

It can be concluded that the maximum stress position of the valve is the upper end of the valve stem. The maximum stress is 8.21 MPa, which is much lower than the allowable stress of the material. The valve has a high safety factor and thus meets the static strength requirements for service.

Meanwhile, the deformation nephograms of the valve were obtained, as shown in Figures 7–9.

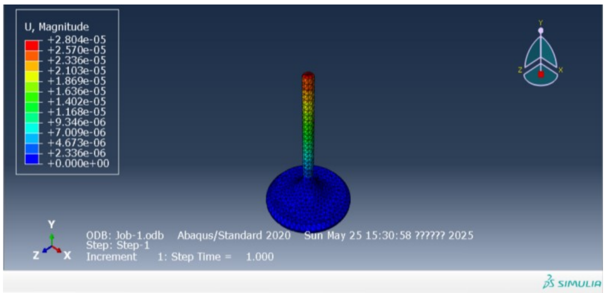

Figure 7: Valve Deformation under Load (First Stage)

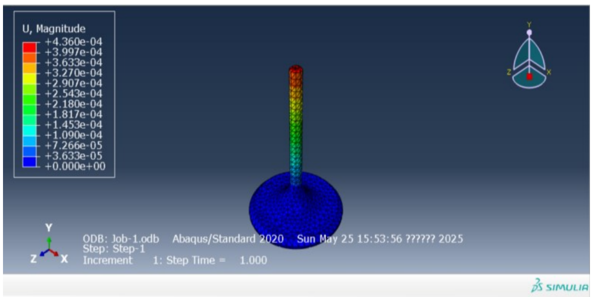

Figure 8: Valve Deformation under Load (Second Stage)

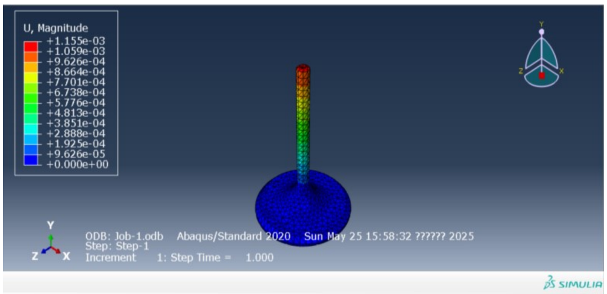

Figure 9: Valve Deformation under Load (Third Stage)

At the rated speed, during the engine operation at different moments, the equivalent stress and deformation of the valve in the cylinder gradually increase with time.

In the first stage, the in-cylinder pressure of the engine is low. The concentrated pressure on the valve is small, and its deformation is negligible.

In the second stage, the force on the valve increases. The valve stem and valve disc bear the main force, and slight deformation occurs.

In the third stage, based on the second stage, the force and deformation increase significantly. The deformation of the valve stem is larger than that of the valve disc. The maximum deformation is 1.1×10^{-3} mm, which is very small, indicating the valve has a high safety factor.

4. Modal Analysis of the Exhaust Valve

Modal analysis of the valve is an important method to avoid valve resonance [15, 16]. As a key moving component controlling cylinder intake and exhaust, the valve operates under complex working conditions, including high-frequency reciprocating motion and high-temperature, high-pressure gas impact. Its natural vibration characteristics directly affect the reliability, economy, and dynamic performance of the diesel engine.

With modal analysis, the natural frequency of the valve can be accurately identified. This prevents resonance between the valve and the camshaft excitation frequency, and effectively avoids serious failure scenarios such as valve stem fracture and valve head fatigue cracking. Based on the vibration mode distribution, optimization can be conducted on the valve stem diameter, head structure, and material matching. This optimization suppresses harmful vibration modes such as bending and torsion, reduces the risks of uneven contact stress and wear between the valve and its guide/tappet seat, and improves the dynamic response accuracy of the valve train.

By constraining the degrees of freedom of the valve in three directions and applying constraint loads, the natural frequency of the valve was extracted. The 1st to 10th order modal shapes of the valve are shown in Figure 10.

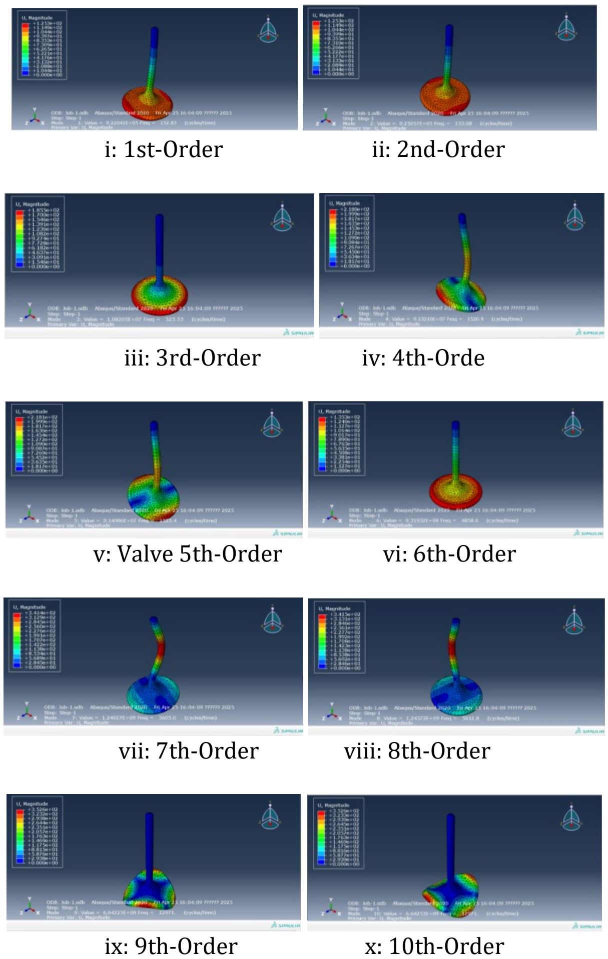

Figure 10: First Ten Orders of Modal Shapes of the Valve

The natural frequencies corresponding to each order of modal shapes are presented in Table 4.

Table 4 Frequencies of the First Ten Orders of Valve Modal Shapes

Order	Frequency/ Hz	Order	Frequency / Hz
1	152.83	6	4858.6
2	153.08	7	5605.0
3	523.53	8	5612.8
4	1520.9	9	12971.0
5	1522.4	10	12971.0

It can be concluded from the above analysis that the first-order natural frequency of the valve is the lowest, at 152.83 Hz. This frequency is far from the frequency corresponding to the engine crankshaft's rated speed of 3000 r/min.

Moreover, the natural frequencies of all orders are basically far from the rotation frequency of the engine crankshaft. Thus, the occurrence of resonance is basically avoided.

5. Fatigue Life Study of the Exhaust Valve

5.1 Fatigue Life Analysis of the 4Cr10Si2Mo Valve

Mechanical fatigue life is defined as the number of cycles or duration experienced by a mechanical structure or component from the start of service to fatigue failure under alternating loads (stress or strain). In this simulation, based on the actual operating characteristics of the valve, the stress-life (S-N) curves suitable for high-cycle fatigue analysis were selected from the built-in material properties of the software. For the correction method, the classical Goodman method was adopted.

Using the load spectra obtained from different operating stages as excitation, the fatigue life study of the valve was conducted using the Fe-safe plug-in in Abaqus software. The study results are shown in Figure 11.

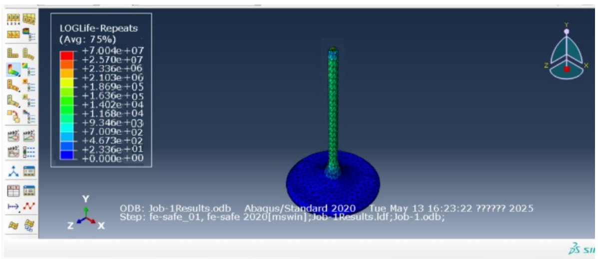

Figure 11: Fatigue Life Nephogram of the Exhaust Valve

It can be seen from the valve fatigue life distribution diagram that the maximum number of cycles in the fatigue life nephogram is approximately 7×10^7. It was calculated via the plug-in that under the working condition of 1000 rpm, the fatigue life of the valve is 2.30×10^4 hours. This means that fatigue failure will occur after the valve operates for 2.30×10^4 hours.

This result is relatively consistent with the research findings in Reference [17], indicating that the designed valve mechanism can meet the fatigue life requirements.

To further enrich the test data, a material optimization method was adopted. Different types of materials were selected to optimize the mechanical properties of the valve, and their impact on the improvement of valve performance was observed. Which provides more theoretical guidance for subsequent valve design.

5.2 Fatigue Life Analysis of the Valve after Material Improvement

In the manufacturing of diesel engine valves, 4Cr9Si2 steel is usually the material with relatively low manufacturing cost [18]. 4Cr9Si2 steel is a commonly used valve steel material. It has good high-temperature strength, oxidation resistance, and wear resistance, which can meet the working requirements of general diesel engine valves.

Meanwhile, studies have shown that TiAl material has significant advantages in the field of high-temperature exhaust valves. It can be used as a preferred solution for the exhaust system of natural gas-fueled diesel engines. Compared with some high-performance alloys, TiAl has lower cost and a relatively mature production process. TiAl-based alloy materials have a low density and can be developed towards lightweighting [19]. ECMS-Ni36 material has the same density as 4Cr9Si2 material, which can be considered to reduce the stress and deformation of the valve [20]. The properties of the above materials are shown in Table 5.

Table 5. Properties of Valve Materials

Mechanical Parameters	4Cr9Si2	TiAl-based Matrix Alloy	ECMS-Ni36
Poisson's Ratio	0.3	0.3	0.3
Density/(kg/m^3)	7780	3800	7800
Young's Modulus /GPa	200	115	200

After optimizing valve materials and conducting comparative FEA following material replacement, the stress distribution, deformation, and vibration characteristics of materials under different working conditions can be accurately evaluated. The performance differences between different materials are compared. Based on this comparison, the valve structure design is optimized—including adjusting structural parameters and achieving lightweighting. Meanwhile, the number of physical tests can be reduced, test schemes optimized, and R&D costs and cycles lowered. This provides scientific basis and technical support for the selection of valve materials and the improvement of their performance.

After conducting finite element analysis on the valve structures made of the above-mentioned materials, the fatigue life analysis results of the valve springs were obtained, as shown in Figures 12–14.

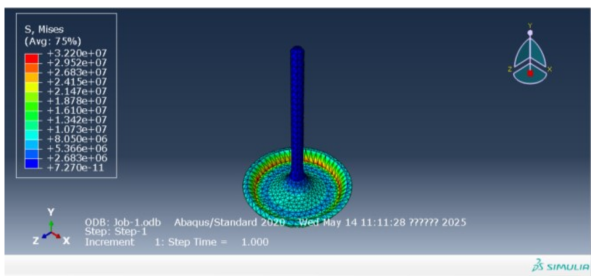

Figure 12: Stress Analysis Nephogram of the 4Cr9Si2 Valve

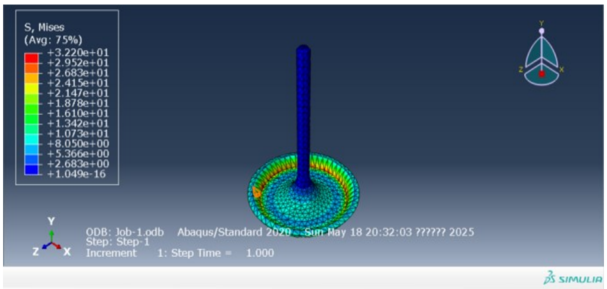

Figure 13: Stress Analysis Nephogram of the TiAl-based Alloy Valve

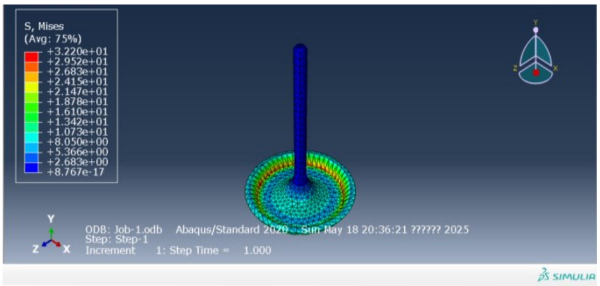

Figure 14: Stress Analysis Nephogram of the ECMS-Ni36 Valve

When comparing the material properties, 4Cr9Si2 steel, TiAl-based alloy, and ECMS-Ni36 show significant differences. Firstly, 4Cr9Si2 steel has a density of 7.7 g/cm^3 and a Young's modulus of 200 GPa, with high stiffness and mature manufacturing processes. However, its high density is a disadvantage for lightweighting. Secondly, TiAl-based alloy has a density of only 3.8 g/cm^3, with significant advantages in specific strength. It can greatly reduce the valve's motion inertia and the overall weight of the engine. Yet, its low Young's modulus limits its deformation resistance under high-temperature conditions. Finally, ECMS-Ni36 has a density similar to that of steel, along with a high modulus of 200 GPa and the characteristics of nickel-based alloys. It exhibits better high-temperature oxidation resistance and creep resistance, making it suitable for stability requirements under extreme working conditions.

The results obtained from static stress analysis confirm the differences in material properties. The stress nephogram of 4Cr9Si2 steel shows local high stress concentration in the transition area between the valve stem and the head. Fatigue damage is likely to occur in this area during long-term service. Due to its low modulus, TiAl-based alloy has a slightly higher overall deformation. Although its vibration characteristics are improved, the risk of seal failure may increase due to insufficient stiffness in high-temperature and high-pressure environments. ECMS-Ni36 has the most uniform stress distribution. Its maximum stress value is reduced by approximately 15% compared with 4Cr9Si2, and the deformation is controlled within a safe range. Its high modulus and creep resistance effectively suppress thermal deformation, ensuring the sealing reliability between the valve and the valve seat.

Considering comprehensively factors such as performance and cost-effectiveness, ECMS-Ni36 emerges as the optimal choice. Although its raw material cost is higher than that of 4Cr9Si2 steel, its life-cycle cost is significantly reduced by reducing maintenance frequency and extending service life. Its high-temperature stability can meet the extreme working condition requirements of diesel engines, without the need for additional structural reinforcement or coating treatment. This simplifies the manufacturing process. Although TiAl-based alloy has outstanding lightweighting effects, it requires surface coatings to make up for its deficiency in high-temperature resistance, resulting in high comprehensive costs and risks. 4Cr9Si2 steel is only suitable for medium and low-load scenarios and cannot meet the requirements of high-performance engines. ECMS-Ni36 achieves the best balance in strength, temperature resistance, and economy, making it an ideal solution for valve material optimization.

6. Conclusions

Based on the existing structural parameters of the valve, 3D modeling of the valve was conducted in SolidWorks software. A new 3D data model was provided for the FEA, fatigue life prediction, and optimization of the exhaust valve, which provided that the most effective way to optimize the fatigue life of the exhaust valve is to modify the exhaust valve tappet and the connection dimensions between the valve and the tappet.

Static stress analysis and modal analysis were performed on the diesel engine valve structure. In the static stress analysis of the valve, the in-cylinder pressure acting on the valve at the rated speed was taken as the main force, with the maximum force being approximately 8.29 MPa. Relevant constraints were set and simulated forces were applied according to the valve's operating conditions, after which the valve stress analysis diagram was obtained. Through modal analysis, the frequency of the valve in the operating environment was calculated and compared with the engine's operating frequency. These analyses ensure the static strength requirements of the valve structure and meet the working condition requirements of avoiding resonance, providing theoretical support for the normal operation of the valve.

Research on fatigue life prediction and material optimization of the valve was carried out. For the valve's fatigue life prediction, it was based on the results of the valve stress analysis, and the Fe-safe plug-in of Abaqus software was used for prediction. The prediction results were imported into Abaqus to obtain the valve's fatigue life nephogram, and finally the valve's fatigue life was determined.

Through material replacement, by comparing the properties and static stress analysis results of the three materials, the optimal material optimization scheme—with ECMS-Ni36 as the optimal material—was concluded. ECMS-Ni36 achieves a good balance among service life, cost, and stability, providing a reliable solution for the design of diesel engine valves.

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