Development of an Algorithm and Creation of a Program for Numerical Studies Based on the Mathematical Model of Torsional Vibrations in Crankshafts of Diesel Locomotive Engines

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**Abstract.** This study shows that the crankshafts of diesel locomotive engines operate under high loads and temperatures. Heat is generated in the contact zones due to friction, which affects the service life and reliability of the crankshaft. This article presents numerical studies on assessing the thermal state and thermal strength of crankshafts for 1A-9DG model diesel engines installed on UzTE16M locomotives. One of the most important indicators for assessing the thermal state of a diesel locomotive engine’s crankshaft is the temperature field that develops in its parts and components. When calculating the effects of contact temperature fields on the crankshaft, the approximation method and iterative method using a program are employed due to the complexity of the design and the inability to obtain accurate calculations of dynamic temperature loading. As a result, a numerical study of the temperature fields that develop during operation on the crankshafts of diesel locomotive engines was carried out. Additionally, an algorithm and program were developed, and numerical studies were conducted in the MATHCAD 15 programming environment. The distribution of volumetric temperature fields in the crankshaft of a diesel locomotive engine is determined based on the Fourier equation, as this shaft is considered a volumetric cylindrical body.

**Keywords:** crankshaft, high load, temperature effect, friction, service life, reliability, strength assessment, numerical studies, algorithm and program, iteration method, approximation method, Fourier equation, stress-strain state of shafts, flowchart, main journal and connecting rod journal, modeling, graph of temperature field changes.

# Introduction

To ensure reliable operation of locomotive crankshafts, it is necessary to study their thermal stability in order to improve their design, manufacturing, and repair technologies.

The long-term service life of crankshafts is determined by the maximum stresses that arise during their operation, particularly bending, torsional, and longitudinal stresses under mechanical influences, as well as thermal strength under the influence of temperature fields. Therefore, the calculation of the stress-strain state can be carried out by analyzing the total stresses and comparing them with the ultimate strength of the shaft material.

Experimental studies of temperature fields and thermal stresses on diesel locomotive crankshafts are dedicated to examining the management of locomotive’s technical operation, which is the main component of the operational process. Diesel locomotive engines must withstand heavy loads and operate efficiently for extended periods. The crankshaft is a crucial part of the engine, subjected to high dynamic loads and temperature effects. Studying temperature fields and thermal stresses is essential for increasing the crankshaft’s reliability and preventing its failure. Temperature fields in the crankshaft: during operation, temperatures vary in different parts of the crankshaft, with the highest temperatures observed in the clutch section and areas connected to bearings. Uneven temperature distribution leads to thermal expansion and the emergence of stresses. Considering the actual technical condition of locomotive diesel engines when planning the repair volume of main locomotive units and assemblies is one of the most important factors for reducing railway operating costs and transportation expenses. Continuous monitoring of the technical condition of operating locomotives is carried out using diagnostic tools and methods. In railway transport, the operation of locomotive thermal power units in a technically faulty state leads to excessive fuel consumption [1]. The use of diagnostic methods in this process allows for identifying changes in the technical condition of thermal power units and recording them when planning repair volumes. Modern diagnostic methods serve to maintain locomotives in good condition.

# Literature review

The heat transfer of diesel engine crankshaft components has been practically unstudied. Therefore, further research on the heat transfer of the crankshaft remains relevant.

The main defects of the crankshaft are microcracks, cracks, damage to the nitride layer, and breakage of the crankshaft-connecting rod mechanism. During the research, a number of issues related to the condition of the crankshaft were examined, resulting in the implementation of a new method for assessing the technical condition of locomotive diesels. This subsequently enabled the analysis of locomotive condition. The operational efficiency of locomotives largely depends on their reliability. Ensuring locomotive reliability is the most critical task of locomotive management. The research is related to the reliability of locomotive diesels and can be applied in testing and diagnosing locomotive diesel crankshafts. Subsequently, it becomes possible to forecast the condition of these locomotive units.

To determine the coefficients of heat transfer from gas to walls. The results of heat transfer studies in 10D100 and PD1M locomotive diesels conducted by G.B. Rosenblatt can be utilized.

To calculate the torsional vibrations of a locomotive diesel’s crankshaft, it is necessary to consider the entire crankshaft-connecting rod mechanism system as a whole.

Strength was verified based on Professor A.I. Gotts’s textbook investigating the kinematics and dynamics of piston engine crankshaft-connecting rod mechanisms, as well as research conducted by M.N. Panchenko to refine the methodology for modeling the dynamics of locomotive diesel crankshaft-connecting rod mechanisms.

The reliability level of diesel locomotives directly affects the performance indicators of the locomotive management. The locomotive management is entitled to maintain an optimal inventory park of diesel locomotives to ensure freight and passenger traffic on routes serviced by locomotive traction. The size of this park is determined based on the turnover of diesel locomotives, calculated for the maximum number of days in the month with peak transportation volumes.

Thus, with a decrease in the reliability level, the inventory park should have a sufficient number of locomotives to ensure the established volume of train traffic on the serviced section. Naturally, this leads to a decrease in the economic efficiency of the locomotive park and negatively affects the overall economic and financial indicators of the management, including transportation costs, labor productivity, and revenue. In this case, the durability of the main components of locomotive diesel engines significantly impacts the efficiency of the locomotive’s power unit. The article by K.A. Ryabko and E.V. Ryabko notes that the most promising method for extending the service life of diesel locomotive cylinder heads is the improvement of hydrodynamic parameters in the cooling cavities between the valves.

This study contributes to this field by providing an integrated approach combining robust modeling, efficient computation, and practical software tools. Several studies provide foundational insight into torsional vibration phenomena in crankshaft systems, particularly within diesel engines, Johnston & Shusto (1987) One of the earliest works using analytical techniques to model crankshaft torsional vibrations, emphasizing the importance of accurate modeling for fatigue prediction [2, 3]. Yamauchi et al. (1999) Combined experimental and computational analyses with a focus on viscous torsional dampers, showing how damping influences vibration amplitudes. Nikishin et al. (2013) Explored a novel approach by correlating cylinder block vibration to crankshaft torsion, offering a less invasive monitoring technique.

Many authors applied advanced numerical simulations and dynamic models to predict or analyze crankshaft behavior under varying conditions, Zhang et al. (2012) and Shou et al. (2011) Explored non-linear torsional characteristics, accounting for complex boundary conditions and variability in displacement, enhancing model fidelity for real-world diesel engines [4, 5]. Mansour & Saleh (2017) Presented a robust finite element analysis (FEA) approach, capturing dynamic responses under realistic engine loads and operating conditions [6]. Ivanov et al. (2017) Conducted experimental and numerical studies, specifically for locomotive diesel engines, offering insights into scaling torsional models for heavy-duty applications. Material properties and damping mechanisms significantly influence vibration behavior, Suh & Park (2014) Assessed material damping and its effect on torsional responses, emphasizing material selection for vibration mitigation [7]. Yamauchi et al. (1999) (listed twice) Reinforced the role of torsional dampers in vibration control, especially under resonance conditions. Advancements in real-time monitoring and control are represented by, Huang & Chen (2021) Demonstrated real-time torsional vibration monitoring using sensor-actuator systems, suggesting improved engine diagnostics and adaptive control capabilities.

Some papers provided comprehensive reviews or contextual studies, Khalil & Farhan (2020) Offered a detailed review of crankshaft dynamics and vibration control methods, identifying trends in research and future challenges [8, 9]. Ablyalimov (2023) Though not exclusively focused on crankshafts, these conference papers provide contextual information about locomotive dynamics, such as support-returning devices and logistics indicators that affect vibration indirectly [10, 11].

In conclusion, scientific literature indicates that while the theoretical foundations and numerical methods for analyzing torsional vibrations are well-developed, their targeted application to locomotive diesel engines requires further refinement and improvement.

# Materials and Methods

## Object Of Research

This research is focused on developing an algorithm and creating a program for numerical studies of the crankshafts of diesel locomotives operating on railway sections of JSC “Uzbekistan Railways”, based on a mathematical model.

The study employed mathematical modeling methods, as well as numerical methods including the Fourier method, Gauss method, and iteration method, along with the software packages SolidWorks and MATHCAD 15. To compare the theoretically obtained results, experimental studies to determine the temperature indicators of locomotive diesel engines were conducted in both laboratory and production conditions, as well as on locomotives equipped with diagnostic complexes.

Technical diagnostics conducted to ensure the required level of reliability and durability of complex objects such as locomotive diesel engines are associated with comprehensive analytical and numerical studies on the mathematical modeling of their parts and components. In this context, an integrated approach involves solving problems related to assessing the stress-strain state, as well as studying the operating modes of locomotive crankshaft systems, during which optimal operating conditions are determined.

One of the main diesel systems where such problems need to be addressed is the most critical and responsible system of the internal combustion engine - the crankshaft-connecting rod mechanism, as it is through this mechanism's parts that the thermal energy of the working gases is converted into the mechanical rotational energy of the crankshaft.

The reliability of the crankshaft-connecting rod mechanism directly determines the reliability and durability of the entire locomotive's diesel engine. This imposes strict requirements on the design, manufacture, installation, operation, maintenance, and repair of the mechanism's parts, as well as on the quality of materials used in the production of these parts. All of these factors should ultimately ensure the required service life of the engine.

# Results and Discussion

Research on developing an algorithm for the mathematical model of torsional vibrations in crankshafts of locomotive diesel engines for the 1A-9DG diesel generator of the UzTE16M locomotive, as well as creating a program for conducting numerical studies, was carried out using MATHCAD 15 software.

Calculation Program (Program 1: “Method for calculating parameters of the torsional vibration model for crankshafts in the 1A-9DG diesel generator of UzTE16M locomotives”).

To develop an algorithm for the mathematical model of torsional vibrations in diesel locomotive crankshafts and to create a digital research program, two main load modes were established based on the crankshaft rotation frequency,  (rpm).

1. at full power - ,
2. at the minimum stable rotational speed of the crankshaft during idle running of a diesel locomotive - , [12].

The algorithm for the torsional vibration model of crankshafts, represented as a discrete system with 8 masses for the 1A-9DG diesel generator of the UzTE16M locomotive, consists of 6 main stages.

Step 1 of the algorithm. Providing (entering) initial data, density for all components of the crankshaft manufactured from alloy steel grade 38XN3MA in accordance with GOST 1050-88 (, ) equal to , the shear modulus (or modulus of elasticity of the second kind) is equal to , when manufacturing a crankshaft from cast iron grade  
VP CHV78-000-87-II, the density (, ) equals to , for cast iron, the shear modulus (or modulus of elasticity of the second kind) is equal to , parameters of the main and connecting rod journals mounted on the diesel engine crankshaft  and  respectively the diameters of the main and connecting rod journals;  and  their lengths, as well *R* - the distance from the axis of rotation of the connecting rod neck to the axis of rotation of the crankshaft passing through its center of gravity, dimensions of the crankshaft connecting rod journals (first and second),  - the thickness, width, and height of the cheek, as well as  and , parameters of diesel engine crankshaft journals - diameter  and length , parameters of flywheel components, its cross-section is divided into 4 basic shapes - outer rim, disk, inner rim, and flange. All necessary geometric parameters are input for these components.

Step 2 of the algorithm. The calculation of the total forces acting on the main and connecting rod journals of the crankshaft was carried out in a crank-connecting rod mechanism. For the normal operation of the crankshaft, the following forces are taken into account. A block diagram was developed for the numerical study of the torsional vibration model of crankshafts in the 1A-9DG diesel generator, designed for the UzTE16M locomotive (Figure 1.).

**BLOCK SCHEME for numerical studies based on the model of torsional vibrations of crankshafts in locomotive diesel engines of the 1A-9DG diesel generator designed for the UzTE16M locomotive**

**START -ВEGIN**

ENTERING INITIAL DATA 1. Parameters of the main and connecting rod journals (first and second) installed on the diesel engine crankshaft; dimensions of the crankshaft nose and flywheel; physical and mechanical properties of the shaft material.

***2,3 - computing modules PROGRAM - 1***

2. Calculation of the total forces acting on the main and connecting rod journals of the diesel locomotive’s crankshaft when operating in the crank-connecting rod mechanism system.  
3. Determination of the mass moments of inertia for all parts of the diesel crankshaft designed for the 1A-9DG diesel generator of the UzTE16M locomotive, as well as the total mass moment of inertia of the entire crankshaft .

***4 - computing modules PROGRAM - 1***

4. Calculation of the torsional stiffness of the main journals for adjacent sections of the crankshaft, as well as the resulting reduced torsional stiffness - .

***5 - computing modules PROGRAM - 1***

5. Calculate the crankshaft oscillation system of a diesel locomotive engine using the Gauss matrix method as an 8-mass discrete system; determine the values in matrix form for equations using  Cramer’s rule.

***6 - computing modules PROGRAM - 1***

Creating graphs and tables, printing tables in the Mathcad 15 programming environment. Analyzing the obtained numerical results and comparing them with the results of experimental studies.

**CLOSING - END**

**Figure 1.** Block diagram for conducting numerical studies on the torsional vibration model of crankshafts in locomotive diesel engines of the 1A-9DG diesel generator designed for the UzTE16M locomotive

Step 3 of the algorithm. Determination of the mass moments of inertia for all components of the diesel engine crankshaft designed for the 1A-9DG diesel generator of the UzTE16M locomotive [13].

Figure 2 shows the total mass moment of inertia along the length of the crankshaft  the diagram depicting the change is shown. As can be seen, the variation in the mass moment of inertia along the length is significant: the maximum mass moment of inertia,  the minimum moment of inertia for mass, .

Step 4 of the algorithm. Torsional stiffness of the main journals for each adjacent section of the crankshaft, as well as mass moments of inertia in the sequential connection of crankshaft sections  The resulting combined torsional stiffness of the connecting rod journals according to the calculation scheme .

Step 5 of the algorithm. Calculation of the crankshaft vibration system of a diesel locomotive engine using the Gaussian matrix method as an 8-mass discrete system includes the following:

- determining the coefficients of the system of equations for 8th-degree polynomials;

- finding the determinant for system coefficients in matrix form;

- matrices according to Cramer’s rule  finding values of the specified form;

- to verify the correctness of the system’s solution by inputting the obtained solutions into the system  to implement by putting into place [14].

Step 6 of the algorithm. Creating graphs and tables in the MATHCAD 15 programming environment, printing tables. Analyzing the obtained numerical results and comparing them with the results of experimental studies.



Maximum mass moment of inertia - . Minimum mass moment of inertia - 

**Figure 2.** Diagram showing the variation of total mass moment of inertia along the length  of the crankshaft

As a result of theoretical and numerical research, the following conclusions were reached:

1. Mathematical modeling of torsional vibrations in diesel locomotive crankshafts was conducted, taking into account the influence of operational loads under conditions of uneven rotation and impacts. An algorithm and program were developed, and numerical studies were carried out in the MATHCAD 15 programming environment.

2. The system was investigated under conditions of uneven rotation of the diesel locomotive crankshaft using Gauss’s matrix method. This was performed for both an accelerated operating mode and a minimum stable frequency idling mode.

Figure 3 shows the oscillation graph of the first connecting rod journal of the crankshaft. This graph shows the accelerated mode under conditions of uneven rotation of the diesel shaft  and at idle  reflects oscillations observed at the lowest possible frequency [15].



, , , 

**Figure 3.** Acceleration mode of the first connecting rod journal during uneven rotation of the diesel crankshaft  and at idle  vibrations at the lowest possible rotational speed

here  - minimum oscillation amplitude,  - the maximum amplitude of oscillation.

Undoubtedly, the uneven rotation mode of the crankshaft leads to its oscillations with high amplitude. In particular, during idling, from the center of the shaft of the first connecting rod journal  if the amplitude of oscillation relative to the *OX* axis constitutes ni in the transitional mode, then in the accelerated mode this indicator  will reach.

Numerical studies on assessing the thermal state and thermal strength of crankshafts for diesel engines of the 1A-9DG model, installed on UzTE16M locomotives, were conducted using the MATHCAD 15 programming environment. Figure 4 of this dissertation presents a block diagram of the “Calculation program for determining the stress-strain state and thermal strength of crankshafts in diesel locomotives with 1A-9DG diesel generators for the UzTE16M locomotive” 2.

A calculation program (PROGRAM 2) for determining the stress-strain state and thermal strength of crankshafts in locomotive diesel engines equipped with the 1A-9DG diesel generator, designed for the UzTE16M locomotive, is presented.

Under the influence of temperature loads, the crankshaft can elongate from the 9th main bearing to the 1st main bearing. To prevent this, the ninth main bearing has durable seals that protect the crankshaft from longitudinal displacement. The power take-off flange is connected to the traction generator by means of a plate clutch, and a combined anti-vibration device is attached to the opposite side of the flange.

Figure 5 shows the results of modeling the contact temperature fields that occur in the cross-sections of a locomotive diesel engine’s crankshaft [16].

 here  – eigenfunctions of the temperature field in the crankshaft material of a diesel locomotive along the z-axis length (here ).

Figure 6 shows a graph depicting the change in overall temperature fields along the length of a steel crankshaft over time t, s, while Figure 7 presents a similar graph for a cast iron crankshaft. As evident from Figures 6 and 7, the temperature fields in the steel crankshaft propagate faster than in the cast iron shaft.

Through analysis of numerical studies conducted in the MATHCAD 15 programming environment, optimal parameters were selected for evaluating the dynamic strength, reliability, and expected service life of diesel locomotive crankshaft components. These parameters were developed to extend their service life and enhance their dynamic properties [17].

**BLOCK SCHEME for numerical studies to determine the stress-strain state and thermal strength of crankshafts used in locomotive diesel engines of the 1A-9DG diesel generator for the UzTE16M locomotive**

**START -ВEGIN**

ENTERING INITIAL DATA 1. Parameters of the main and connecting rod journals of the crankshaft, as well as the connecting rod bearings (first and second), dimensions of the shaft nose and flywheel; physical and mechanical properties of the shaft material and thermal strength indicators.

***2,3 - computing modules PROGRAM - 2***

2. Inputting the parameters of the heating source that generates a temperature field at the nose of the crankshaft when *L=0*; ;

3. Calculation of the temperature field variation along the crankshaft of a diesel locomotive, *z* (here ). Calculation of the eigenfunctions of the temperature field along the length z in the material of a diesel locomotive’s crankshaft 

4. Calculating the change in the temperature field over time *.*

***4,5 - computing modules PROGRAM - 2***

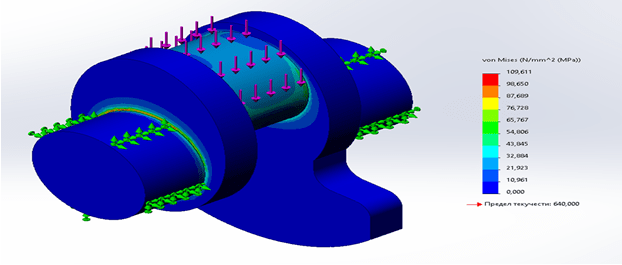
5. Calculation of the total deformation caused by contact temperature fields arising along the length z of a diesel locomotive’s crankshaft (here ) and by time ,

***6,7 - computing modules PROGRAM - 2***

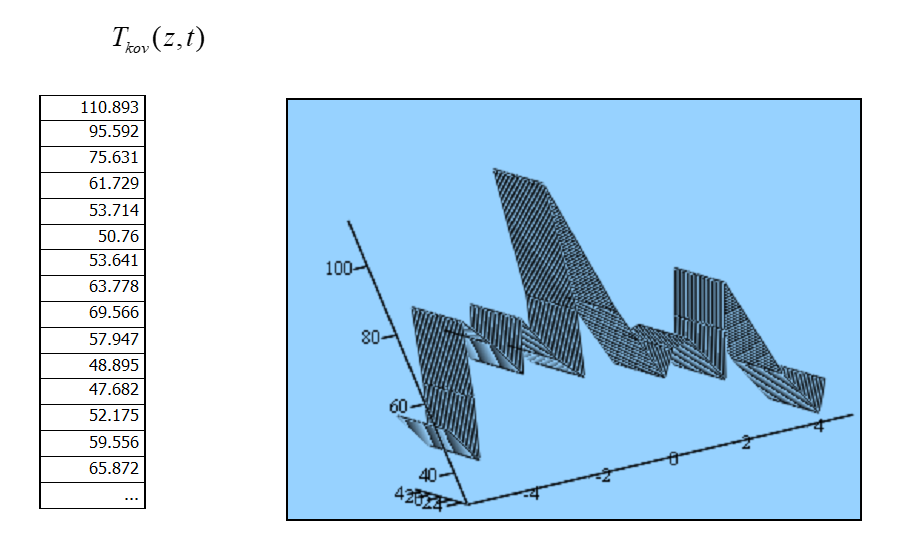
Calculate the overall stress-strain state and verify the strength condition based on formulas. Assess the fatigue resistance and longevity of locomotive crankshaft components using formulas. Determine the endurance limit of crankshaft parts using formulas, and calculate the longevity of shaft components using formula. Compare the results with experimental data.

**FINISHED - END**

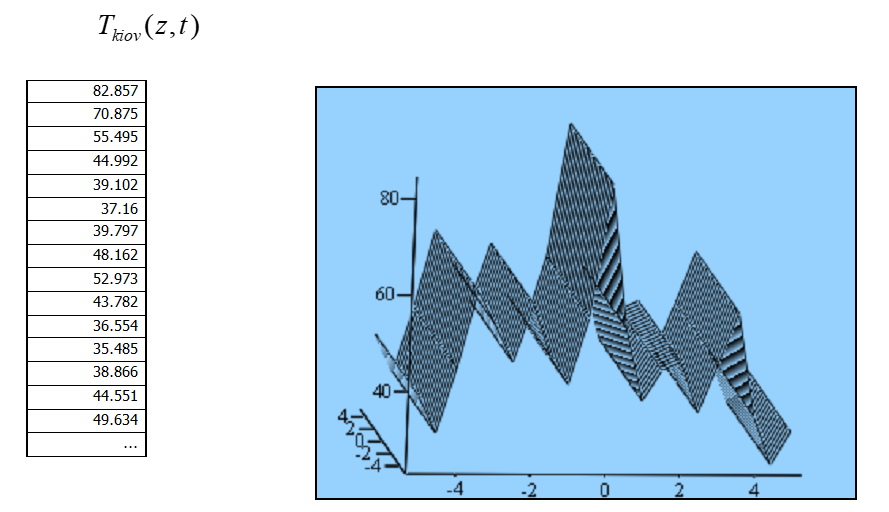
**Figure 4.** Block diagram for determining the stress-strain state and thermal strength of the crankshafts of diesel locomotive diesels of the 1A-9DG diesel generator for the UzTE16M diesel locomotive



**Figure 5.** Results of modeling temperature  fields generated in cross-sections of a diesel locomotive’s crankshaft

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**Figure 6.** Graph showing the variation of overall temperature fields along the length  of a steel crankshaft as time *t* changes in seconds

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**Figure 7.** Graph showing the change in overall temperature distribution along the length of the cast iron crankshaft as a function of time t in seconds

# Conclusion

During diesel engine operation, the crankshaft is subjected to gas pressure forces as well as inertial forces of reciprocating and rotating parts. These factors generate significant torsional and bending stresses, accompanied by vibrations, which lead to variable pressure, friction, and fatigue wear. Under operating conditions, large cyclic loads arising from bending and torsional vibrations can result in shaft failure. Therefore, despite its relatively small mass (approximately 15% of the engine mass), the crankshaft must demonstrate high strength, rigidity, and wear resistance of its friction surfaces. For this reason, crankshafts are typically manufactured from high-quality carbon or alloy steels by forging or stamping, or cast from high-grade cast iron or steel.

In this study, a comprehensive approach was applied to assess the stress–strain state and to investigate the operating modes of the diesel locomotive crankshaft. It was found that optimal operating modes could be determined by numerical analysis. The thermal state of the cylindrical crankshaft was evaluated for all operating regimes of the diesel locomotive engine. The results show that numerical modeling of contact temperature fields provides reliable information on the distribution of thermal loads along the shaft. An algorithm was developed and implemented in the MATHCAD 15 environment, and a flowchart was created to perform numerical studies for evaluating stress–strain and thermal strength characteristics of crankshafts in diesel locomotive engines equipped with a 1A-9DG diesel generator of the UzTE16M locomotive.

Furthermore, numerical simulations of the contact temperature fields in various crankshaft cross-sections were carried out, and graphs illustrating the evolution of temperature fields along the length of both cast-iron and steel crankshafts were obtained. A comparative analysis of experimental and numerical data confirmed the adequacy of the proposed model. It can be concluded that the developed methodology allows for a reliable prediction of the  
stress–strain state and thermal behavior of diesel locomotive crankshafts, thereby providing a scientific basis for enhancing their operational reliability and durability.

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