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PISTON SCRAPER RING LIFETIME PREDICTION BY MODELING AND NUMERICAL ANALYSIS

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Abstract: *The internal combustion engines represent the main power source for vehicles and for different machineries, including electricity generators. Even if the strict regulations are punishing the engines and claims their retirement, they will continue to be used on vehicles, especially for the hybrid ones and also for the machineries for where other solutions cannot be efficient. This paper addresses the scraper rings behavior using finite element modeling and analysis and their lifetime using numerical predictions. This study includes modeling different piston scraper rings shapes and approaching materials depending on the fuel used, gasoline or diesel. The lubrication performances are considered, together with the possibility to use different materials for manufacturing the scraper rings.*
Keywords: *scraper ring, internal combustion engine, fatigue prediction, lifetime, finite element modeling and analysis.*

1. INTRODUCTION

Higher performance and quality of auto pieces have always been a requirement in automobile industry. Hence, developing lighter and stronger structural components based on new materials is vital for its use in new vehicles [1]. Moreover, the engine is known to be one of the most important parts for the vehicles. Thus, developing accurate life prediction models of its components is a key to study the fatigue behavior [2-4] and propose higher performance solutions under the evidence of ensuring safety. In the case of engine components, high-strength materials - mainly steels - combined with special mechanical and/or thermal surface treatments are applied to manufacture scaled-down components to withstand the expected portion of the vehicle's life.

The most damaged components inside the engine are its piston rings that perform large displacements and undergo normal multiaxial cyclic and shear stresses during operations [5-7].

Piston rings have been formed with pronounced nitriding surface treatment [8]. This process is a nitrogen supply and a steel hardening in a temperature of 500°C to 520°C with a treatment time of 1 to 100 hours (gas nitriding for segments) [9, 10]. Figure 1 shows an ordinary model of the segments with five rings where two are similar with an aperture measurement and a ring with an irregular shape. The latter will be the subject of the current study.

Fig.1. Piston rings models (gasoline engine)

The ring set consists of five or three rings that are assembled on the grooves of the piston with very precise clearance. Piston rings must respect certain characteristics in order to guarantee a good operation and a good lifetime. Among the causes of the rings fatigue, a bad positioning in the phase of assembly which can form a beginning of cracking, a non-observance of the plays, and mainly a beginning of cracking which appears at their first assembly. The pistons rings life cycle is decreasing because of the following major causes, that are presented below:

1. The high temperature while operation – the wear and fatigue of the piston rings accelerates while being exposed to high temperatures that is met inside the combustion chamber, due to the high thermal stresses;

2. Combustion by-products and contaminants – the presence of different combustion by-products, such as soot, carbon deposits, and acids are leading to ring sticking, increased friction, and accelerated wear;

3. Insufficient/inadequate lubrication or the presence of contaminants in the lubricating oil – increasing friction and wear between the rings and cylinder wall are leading to reduced life cycle;

4. Poor ring design or material selection – the insufficient hardness is compromising the ring's ability to withstand the mechanical and thermal stresses encountered during engine operation;

5. The cylinder wall condition – the unwanted surface is causing abnormal wear patterns and is leading to premature fatigue and reduced performance;

6. Inappropriate maintenance and service operations – the regular oil changes is mandatory for the engine long life, while the unproper engine tuning and services are decreasing the engine life cycle.

In addition, the major causes of rings life cycle decreasing include also:

- Gumming,
- Pinching,
- Poor cutting clearance,
- Heavy runout (poor transition from bottom to top dead center),
- Twisting of the ring,
- Axis measurements before segment assembly,
- Fragility of the segment during hand assembly.

The numerical method [5, 11-14] can be used to define the most defective areas in a ring that is sensitive to those causes.

In this paper, evaluation of the fatigue life [15-17] of a hot-formed piston rings with pronounced surface treatment, based on Finite Element Method (FEM) is proposed. Firstly, a statistical study using survey has been performed to extract the most defective part among engine pieces with higher fatigue behavior. Secondly, a numerical software has been used to model the complex shape of the ring to study its fatigue behavior. Thirdly, by using the FEM fatigue prediction model, the fatigue life contour showing the part with the higher fatigue of the ring is extracted.

2. MATERIEL AND METHODS

The engine is the core system of a vehicle, consisting of the mechanism made of many elements where the pistons, the frames and the cylinder form the principal components [18]. For this purpose and to define the most defective part among the engine pieces, a survey has been carried out. On one hand, a statistical method based on a survey which was filled with various profiles in automobile industry is approached. After collecting the data, a program code is used to analyze the data. The Python program code established to schematize the results is as follow:

```
import pandas as pd
import matplotlib.pyplot as plt
data=pd.read_excel(r"C:\Users\infoservice\OneDrive\Bureau\new_Voiture.xlsx")
plt.xlabel('les pannes')
plt.ylabel('fréquence')
data ['Les pannes les plus fréquentes'].value counts().plot(kind='bar',color='g');
```

The program code facilities the analysis and the interpretation of the survey data. Based on that, the engine performance and the possible defective parts inside the engine are obtained. In addition, the most stressed parts by the fatigue phenomenon are also highlighted.

The equation (1) was also used to study the fatigue behavior:

$$\nabla . S + F_v = 0 \quad (1)$$

where S is the second Piola-Kirchhoff stress [19, 20]. Fundamentally, this is the equation of motion: divergence of stress equals the volume force. The discretization of this equation using finite element method allows to propose a fatigue prediction model. Meanwhile, to take in consideration the material used in the simulation, material properties as density (in Kg/m3), Young's modulus (in Pa) and Poisson's ratio were introduced to the FEM model. These properties depend on ring choice.

During this part of study, the focus is on the scraper rings used for gasoline engine.

Scanning Electron Microscope (SEM) method was used to detect the real material from which the scraper rings are manufactured. The chemical composition of the ring is determined after polishing the specimen taken for the scraper ring used for study and analyzing it using the microscope.

For example, rings can be built in either:

- Grey cast iron: GG25,
- Ductile iron: GGG50,
- Bronze: CuSn7 and CuSn10,
- Steel: 54SiCr6,
- Stainless steel: X90CrMoV18.

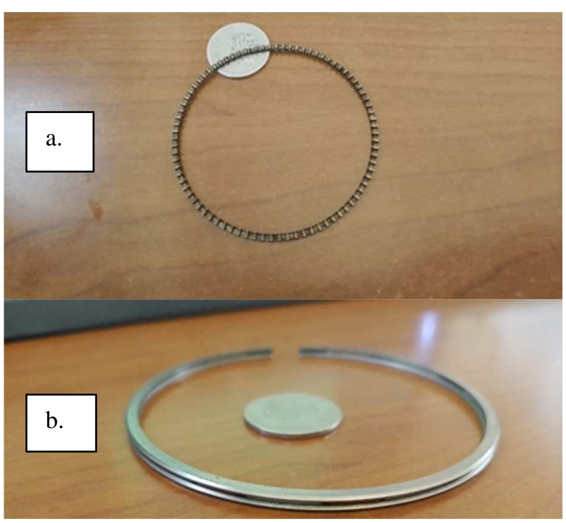

Fig.2. a. The scraper ring for a gasoline engine, b. Scraper segment for a diesel engine

Fig.3. The polishing tool

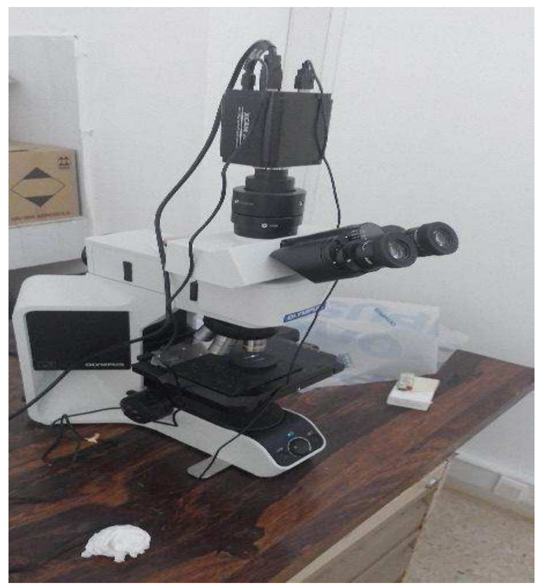

Fig.4. The experimental equipment - Scanning electron microscope (SEM)

It is noted that the most common stainless steel is 12X18H10T. In the same way, the volume force was taken in consideration in the proposed FEM model by specifying the direction of a force per unit area (in N/m2). The approached force direction for the investigated piston rings is presented in Figure 5.

In this way, the overall fatigue behavior in terms of stress reasons was modeled significantly. The developed FEM model was used to compute the fatigue life contour of the piston ring by using the discretization of equation (1).

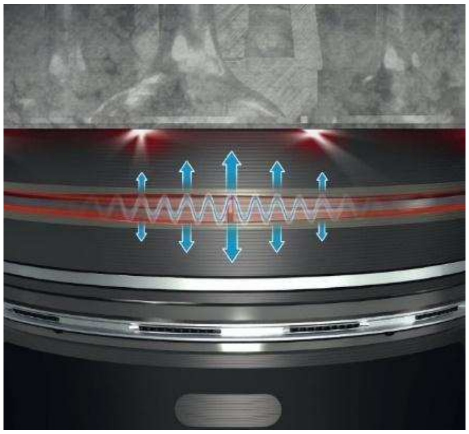

Fig.5. The force direction experienced by the piston rings [21]

The part design was created using computer-aided design (CAD) software (figure 6), and the actual dimensions of the scraper ring, corresponding to a gasoline engine, as presented in the table 1.

Table 1 **Dimensions of the scraper ring (in mm)**

D_{int} [mm]	D_{ext} [mm]	Height [mm]	Width [mm]
62.00	64.00	2.00	2.00

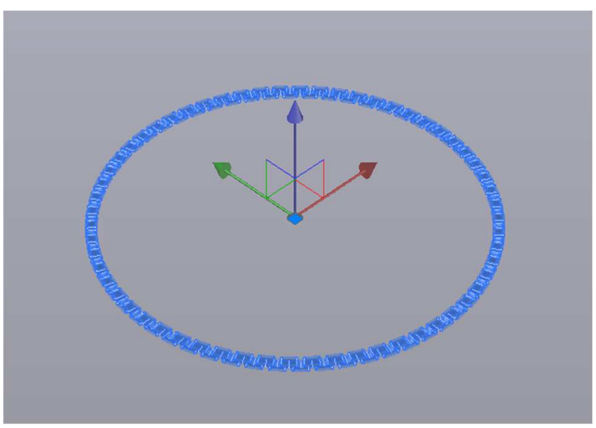

Fig.6. The CAD design of scraper ring for a gasoline engine

The model was imported into the finite element calculation software, where the appropriate material was defined using the corrective mechanical characteristics of the material described using SEM, as well as the boundary conditions exerted on the part during operation (figure 7).

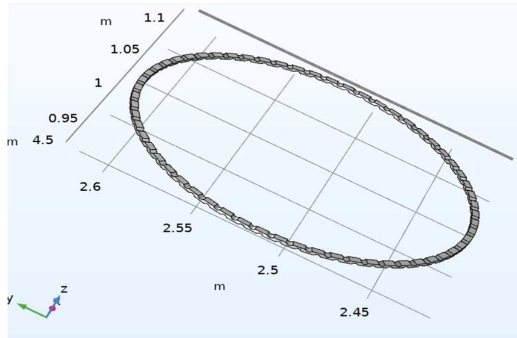

Fig. . The imported scraper ring into the FEM Software

Meshing was performed on the scraper ring (figure 8) while the properties had been determined to keep calculation time to a minimum. Regular wicks were chosen which, however, enabled the results to be clearly visualized in order to define the zones most affected by fatigue and stress phenomena according to von Mises' law.

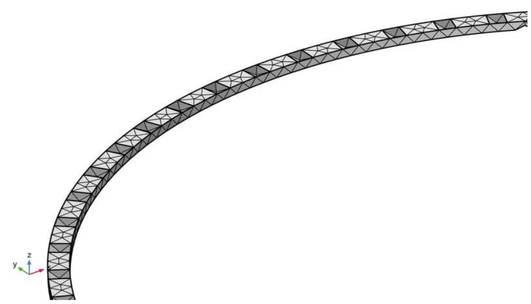

Fig.8. The generated mesh using FEM

After generating the mesh for the current study case and applying the appropriate boundary conditions, the simulations were initiated by solving the equations of motion.

In this situation, the second Piola-Kirchhoff equation or the general equation of motion is applied. The second Piola-Kirchhoff equation is a constitutive equation commonly used in solid mechanics to describe the behavior of materials undergoing large deformations. It relates the stress tensor (second Piola-Kirchhoff stress) to the deformation gradient tensor and material properties. By solving this equation, the response of the piston ring under applied loads and deformation can be determined.

Alternatively, the general equation of motion can be employed to capture the dynamic behavior of the piston ring. This equation, which is derived from Newton's second law of motion, relates the applied forces and resulting accelerations. By solving this equation, the motion and response of the piston ring can be simulated and analyzed.

Both approaches allow for the numerical simulation of the piston ring's behavior under various loading conditions and enable the prediction of its response, including stress distribution, deformation, and fatigue life estimation.

By solving these equations iteratively and considering the material properties, boundary conditions, and applied loads, researchers can gain valuable insights into the structural behavior of the piston ring and make informed decisions regarding its design and optimization.

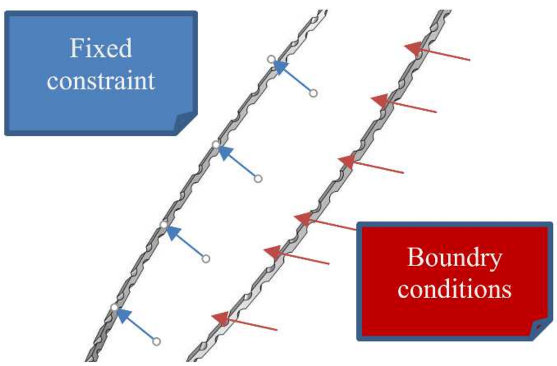

Fig.9. Applied load distribution on the scraper ring from a gasoline engine

3. RESULTS AND DISCUSSION

To determine the specific component that would be the subject of the current research, a diverse range of responses were collected through the survey. However, the analysis of the survey results revealed that the component with the highest fatigue behavior within the engine was the piston rings.

This finding establishes the prominence of piston rings as a critical factor in engine failures. Figure 10 visually represents the outcomes of the statistical study based on the survey data, clearly demonstrating that piston rings are more significant contributors to engine failures compared to even engine cooling systems. The identification of piston rings as a primary cause of engine failures highlights their crucial role in the overall performance and reliability of the engine. Consequently, understanding and addressing the factors affecting the fatigue behavior of piston rings becomes paramount in ensuring optimal engine functionality and durability. The current research aims to delve deeper into the study of piston rings, investigating their performance, potential failure modes, and proposing effective strategies to enhance their longevity and mitigate the associated risks.

The piston rings are to be considered the most important cause of engine failures most even than engine cooling (figure 10).

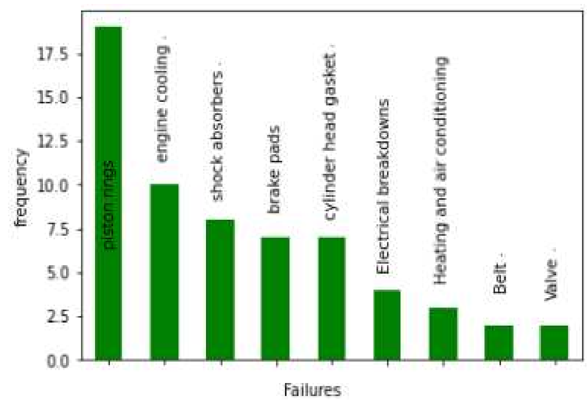

Fig.10. Frequency of engine failures causes

It is noted that also based on a literature review, the piston rings are among the most mentioned pieces in the field of mechanical fatigue that support the above statistical study.

The results of the Scanning Electron Microscopy (SEM) test are shown in the figure 11:

Fig.11. Basic material composing the ring

The physical parameters (chemical compositions) used during this research are shown in table 2:

Table 2

Chemical compositions (weight %)

Elements	C	Cr	Ni		Mo	Mn	Si
%	0.41	0.85	1.62		0.26	0.78	0.33

The material standard properties (mechanical) used in the current FEM model are [22]:

- Young's modulus: 197.6 GPa
- density ρ: 7.9 $kg/dm3$
- Poisson's ratio: 0.247s

Furthermore, the clearance between the piston ring and the groove in which it is positioned is an essential parameter of the model. The required clearance, after expansion, is subjected to specified tolerances [23]:

- Tolerance Lower Limit (TLow): 3.5/1000 mm
- Tolerance Higher Limit (THigh): 5/1000 mm

These tolerance values are crucial in ensuring proper functioning and longevity of the piston rings when installed within the engine. The fatigue life of the segment under radial load, as computed by the proposed FEM model, is graphically presented in Figure 12. This figure presumably illustrates the relationship between the applied radial load and the predicted fatigue life of the segment. The FEM model enables researchers to assess and analyze the structural integrity and performance of the segment, thereby providing valuable insights into its potential fatigue behavior under various operational conditions.

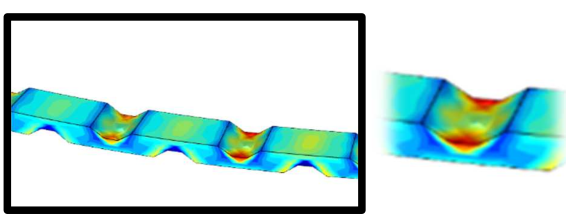

Fig.12. Fatigue life contour predicted by the numerical simulation model for an example segment

The results of the fatigue simulation analysis show that the fatigue life of the thinnest area of the ring, that is the area that allows oil distribution, is the lowest in the radial fatigue test. The fatigue crack appears first, therefore the most dangerous area is the one close to the ring that is the subject of the current study.
In the simulation analysis of the radial fatigue test, the predicted locations of the minimum fatigue life are all in the groove part made to fluidize the oil passing, whether the casting defects are considered or not. But in the simulation analysis of the fatigue test considering the casting defects, the minimum fatigue life appears outside the two connected spokes, as shown in Figure 12.

Based on the obtained results from the current study, exploring alternative shapes and materials for piston rings can be a promising avenue to propose innovative solutions that extend their lifetime in the future. The findings and insights gained from the research provide a valuable foundation for further investigations and experimentation.

By testing different shapes of piston rings, such as variations in the cross-sectional design or surface features, researchers can explore how these modifications impact the fatigue behavior and overall performance of the rings.
This experimental approach allows for the identification of shapes that can potentially enhance the load distribution, reduce stress concentrations, or improve the sealing properties of the rings, thus contributing to their extended lifespan. Additionally, considering alternative materials for piston rings opens possibilities for improving their fatigue resistance and durability. Exploring advanced materials with enhanced mechanical properties, such as high-strength alloys or composite materials, can provide new insights into their performance under various operating conditions. These materials may exhibit superior resistance to wear, corrosion, and thermal stresses, thereby increasing the longevity and reliability of piston rings in engine applications.

By combining the knowledge gained from the current study with experimental investigations of new shapes and materials, researchers can propose innovative solutions to enhance the lifetime of piston rings.

This iterative process of testing, analyzing, and refining designs will contribute to the ongoing advancements in piston ring technology, ensuring improved performance, reduced maintenance, and enhanced reliability in future engine systems. However, with the described materials and methods, the aim would generally be to improve the fatigue resistance and performance of the piston rings. The use of advanced materials, such as high-strength alloys or composite materials, along with optimized ring shapes, can potentially enhance the longevity and reliability of the rings. These improvements may include:

1. Increased fatigue life: the new materials and optimized designs may result in piston rings that can withstand a greater number of cyclic loading cycles before failure, thereby improving their fatigue resistance;
2. Enhanced durability: the use of advanced materials can provide improved wear resistance, reducing the likelihood of premature wear and degradation of the piston rings;
3. Improved sealing performance: optimized ring shapes can enhance the sealing properties of the rings, leading to better compression and reduced gas leakage, ultimately improving engine performance and efficiency;
4. Reduced maintenance and downtime: by increasing the lifespan of the piston rings and minimizing the occurrence of failures, the need for frequent replacements and maintenance can be reduced, resulting in improved reliability and reduced downtime for engine servicing.

It is important to note that the specific results achieved would depend on the specific materials, designs, and testing procedures employed in the study. Further research and experimental validation are necessary to obtain quantitative results and assess the effectiveness of the proposed materials and methods in extending the lifetime and performance of piston rings.

4. CONCLUSIONS

In this paper, an extensive statistical analysis that sheds light on the engine component exhibiting the highest fatigue behavior were presented. By harnessing the valuable insights provided by a diverse range of automotive experts, including ordinary drivers, professional drivers, mechanics, and mechanical engineering students, a comprehensive understanding of the challenges faced by these components in real-world scenarios have been obtained. Through a meticulous selection process, the scraper ring piston as the focal point of the current investigation was identified. This critical component plays a crucial role in the engine's performance, and its fatigue behavior has significant implications for the overall reliability and durability of the system. To establish a solid foundation for the numerical analysis, a detailed geometrical modeling phase was developed, ensuring that the chosen ring's exact shape and dimensions were accurately considered. This meticulous approach allowed to capture the intricate geometrical features of the component and lay the groundwork for subsequent investigations. In addition to the geometrical modeling, the Scanning Electron Microscopy (SEM) method was applied to delve into the chemical composition of the ring. By examining the elemental composition and microstructural characteristics, valuable insights into the material's properties and its potential impact on fatigue behavior were gained. Building upon this foundation, a sophisticated lifetime numerical prediction model using the powerful Finite Element Method (FEM) was developed. This advanced computational approach allowed to simulate and analyze the component's fatigue behavior under various operating conditions and stress levels. Through these simulations, the thinnest areas of the ring as the most vulnerable to fatigue failure, providing crucial insights for future design enhancements and optimization strategies were identified. This research paves the way for exciting future avenues of exploration. This research findings contribute to the advancement of automotive engineering, with the aim of developing safer, more reliable, and more efficient vehicles. By addressing the challenges posed by fatigue behavior in engine components, the current research strives to make significant contributions to the automotive industry, benefiting both manufacturers and end-users alike.

5. FUTURE WORK

Proposing alternative materials to replace the existing base material for the piston rings holds the potential to offer a higher level of fatigue resistance. However, to validate and verify the numerical results obtained from simulations, the development of a small-scale fatigue test bench prototype becomes crucial. This experimental setup will allow for the practical evaluation of the proposed materials and their performance under realistic operating conditions. By conducting fatigue tests on the prototype, researchers can validate the numerical predictions and gain valuable insights into the actual fatigue behavior of the rings.

Moreover, further investigations should be conducted to explore alternative ring shapes that can potentially improve fatigue resistance. By exploring different geometries and profiles, researchers can identify designs that distribute stresses more effectively, minimize stress concentrations, and enhance the overall performance of the rings. This iterative process of design refinement can significantly contribute to extending the lifetime of the rings and improving their fatigue resistance.

Additionally, incorporating advanced materials into the design of piston rings offers promising possibilities for mitigating fatigue-related issues. The utilization of advanced materials, such as high-strength alloys, composites, or surface coatings, can provide enhanced mechanical properties and improved resistance to fatigue, wear, and other degradation mechanisms. Exploring and evaluating these materials through experimental testing and numerical simulations can provide valuable insights into their applicability and performance in real-world engine conditions.

By pushing the boundaries of design and material science, researchers can unlock new possibilities for enhancing the longevity and performance of engine components, including piston rings. The integration of experimental validation, innovative ring shapes, and advanced materials will contribute to the development of more reliable and durable engine systems, ensuring improved efficiency, reduced maintenance, and increased safety.

6. AKNOWLEDGMENT

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Predicția duratei de viață a segmentului de ungere prin modelare și analiza numerică

Motoarele cu ardere internă reprezintă principala sursă de energie pentru vehicule și pentru diferite utilaje, inclusiv generatoare de energie electrică. Chiar dacă reglementările stricte pedepsesc motoarele termice şi pretind retragerea lor, acestea vor continua să fie folosite pe vehicule, în special pentru cele hibride şi, de asemenea, pentru utilajele pentru care alte soluţii nu pot fi eficiente. Această lucrare abordează comportamentul segmenților de ungere folosind modelarea și analiza cu elemente finite şi durata de viaţă a acestora folosind predicţii numerice. Acest studiu include modelarea diferitelor forme de segmenți de ungere ai pistonului şi abordarea materialelor în funcție de combustibilul folosit, benzină sau motorină. Sunt luate în considerare performanțele de lubrifiere, împreună cu posibilitatea de a folosi diferite materiale pentru fabricarea segmenților de ungere.

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