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Comparative Study on Transmission Performance of Manganese Phosphate Coated Gears

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Abstract: As an important part of transmission systems, coatings can improve the physical properties of gear surface. It is meaningful to research the effect of coating on the transmission performance of gears. In this paper, eight-degree-of-freedom dynamic response model of helical cylindrical gear is established considering friction, and the influence of friction factors on dynamic response is explored. The tribological properties and lubrication characteristics of the coating are investigated and compared with uncoated. The transmission performances of manganese phosphate conversion coated gears are studied experimentally. The results show that the coefficients of friction of Mn–P[C] coatings are reduced by 19%, the average amplitude and root mean square of vibration acceleration are obviously decreased, and the transmission efficiency is improved. The manganese phosphate conversion coating is beneficial to the transmission performance of gears.

Keywords: manganese phosphate coating; tribological property; transmission performance; vibration response

Citation: Li, G.; Chen, Y.; Zang, L.; Liu, R.; Ju, D.; Wu, Y.; Tan, Y. Comparative Study on Transmission Performance of Manganese Phosphate Coated Gears. *Coatings* **2021**, *11*, 1026. https://doi.org/10.3390/coatings11091026

Academic Editor: Diego Martinez-Martinez

Received: 29 July 2021
Accepted: 23 August 2021
Published: 26 August 2021

1. Introduction

Gear transmission systems are widely applied in the mechanical transmission field of automobiles, rail transit, ships and aircrafts, owning to the advantages of excellent transmission stability and efficiency [1,2]. With the development of new energy vehicles, extra requirements are put forward for the gear transmission systems, such as heavy load, high speed and light weight. The performance of the gear tooth surface has an important influence on the improvement of gear transmission performance [3,4]. The research shows that the tribological properties between gear surfaces can prolong the fatigue life and improve the transmission efficiency of gears. Gear coating surface strengthening technology is a feasible and effective solution [5–7].

The development of surface coating technology improves the friction and lubrication environment between tooth surfaces, which also provides a new way to further extend the service life and transmission performance of gears [8,9]. The coated gear can significantly improve the load-carrying capacity of the tooth surface and fatigue life of gears, but the research on the influence of the vibration characteristics of the transmission system is less. The vibration mechanism of coated cylindrical helical gear is very complex, which is closely related to the dynamic behavior of gear [10,11]. Therefore, it is meaningful to study the transmission performance of coated gear in practical application environment.

The manganese phosphate conversion coatings have the function of wear resistance and lubrication during gear meshing [12–14]. Coating characterization usually includes microstructure, coating thickness, surface morphology, mechanical properties and bonding strength. Manganese phosphate conversion coating on the surface of alloy steel substrate can effectively reduce the friction coefficient [15,16]. In order to improve the fatigue life of gears, manganese phosphate conversion coating as a solid lubricating coating has been applied to gear transmission, and excellent practice has been achieved [17]. Moreover, experimental results show that manganese phosphate coating of different thickness also have certain effects on the fatigue life of gears [18]. The engineering application test research of the coating on the performance of gear transmission efficiency and vibration response is worthy of further discussion.

The dynamic vibration characteristics are related to variable mesh stiffness, coefficient of friction (COF), backlash and transmission error [19,20]. The time-varying mesh stiffness is one of the key factors to study the dynamic response of coated gears. Finite element method [21–23], analytical method [24,25] and software simulation method are applied to calculate the mesh stiffness excitation [26]. There is few experimental study on the transmission performance for the coated gears.

The dynamic model of multi degree of freedom (DOF) gear system considering multi factors can effectively reflect the dynamic characteristics of gear. Xiao et al. [4] established the dynamic model of 6-DOF coated spur gear, and analyzed the influence of coating on the amplitudes of vibration displacements and velocities of gear transmission system. Wang et al. [27] built an 8-DOF spur gear system, and the nonlinear characteristics of the system were characterized by bifurcation diagram, Poincare map and spectrum diagram. A 6-DOF dynamic model of helical gear is obtained [28], including torsional, bending and axial coupling motion of helical gear system. Meanwhile, the influences of dynamic transmission error of helical gear on vibration stability are analyzed. Jiang et al. [29] presented a 6-DOF helical gear model considering time-varying sliding friction and mesh stiffness, which was used to simulate the dynamic characteristics of spalling helical gear pair. The results show that the sliding friction has an effect on the frequency domain response of the helical gear, and increases the peak to peak value of the vibration response.

Reviewing amounts of related literature scholars and researchers mainly used dynamic simulation methods to build dynamic model of gear system and analyze gear response characteristics. Compared to the uncoated gear, the manganese phosphate coated gear has an important influence on the friction characteristics and elastic modulus of the tooth surface. Therefore, it is very important to study the influence of coating factors on the transmission performance of helical gear in industrial application.

Driven by the motivation mentioned above, herein, a dynamic model of 8-DOF coated helical cylindrical gear is established considering tooth surface friction, mesh stiffness, transmission error and damping, and the influencing factors of gear dynamic response are analyzed. The friction characteristics and elastic modulus of coated alloy steel were obtained through experiments, and the appropriate coating thickness guides the preparation of manganese phosphate conversion coated gear. The transmission performances including running-in performance, efficiency, average amplitude and root mean square value of vibration acceleration are compared and analyzed between uncoated and manganese phosphate coated transmission gears. The results show that the manganese phosphate thick coating can reduce the vibration acceleration response and improve transmission efficiency.

2. Dynamic Model of Helical Gear

Sliding friction has been reported to be an important factor of gear vibration and noise. As helical cylindrical gear rotating, the gear meshing will produce axial dynamic meshing force due to the spiral angle. When analyzing tooth friction, the system should consider the longitudinal vibration (X direction). Thus, the meshing bending–torsion–axial coupled vibration model of gear system is established. A rigid body dynamics model with 8-DOF for helical cylindrical gear considering tooth surface friction is shown in Figure 1.

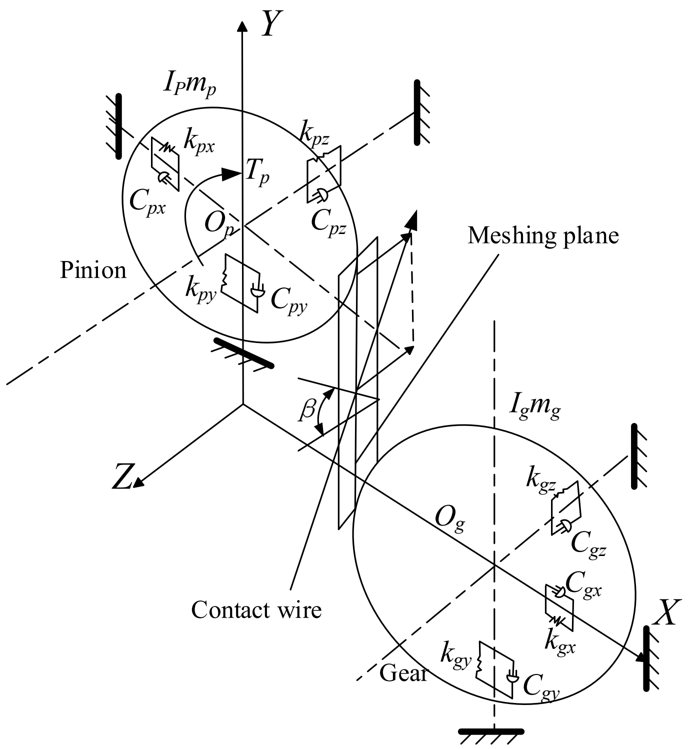

Figure 1. Nonlinear dynamic model of cylindrical helical gear transmission.

Ignoring the support of the bearing and the box, the helical gear transmission system is simplified as a mass-spring damping system. Each gear contains one degree of freedom rotating around the Z axis and three translational degrees of freedom along the X, Y, Z direction, respectively. The system includes helical gear mass, rotational inertia, stiffness, damping and base circle radius.

The generalized displacement array of vibration system in three-dimensional space is:

$$\{\delta\} = \{x_p\ y_p\ z_p\ \theta_p\ x_g\ y_g\ z_g\ \theta_g\}^T \tag{1}$$

where x_i, y_i, z_i, θ_i $(i = p,g)$ is the vibration displacement in X, Y, Z direction and torsional vibration displacement in Z direction at the midpoint Op and Og of the pinion and driven gears, respectively.

The 8-DOF dynamic equation of cylindrical helical gear is expressed as the following:

$$\begin{cases} m_p\ddot{x}_p + c_{px}\dot{x}_p + k_{px}x_p = F_{px} \\ m_p\ddot{y}_p + c_{py}\dot{y}_p + k_{py}y_p = -F_{py} \\ m_p\ddot{z}_p + c_{pz}\dot{z}_p + k_{pz}z_p = -F_{pz} \\ I_p\ddot{\theta}_p + F_{py}R_p - (R_p\tan\alpha - H)F_{px} = -T_p \\ m_g\ddot{x}_g + c_{gx}\dot{x}_g + k_{gx}x_g = -F_{px} \\ m_g\ddot{y}_g + c_{gx}\dot{y}_g + k_{gy}y_g = F_{py} \\ m_g\ddot{z}_g + c_{gz}\dot{z}_g + k_{gz}z_g = F_{pz} \\ I_g\ddot{\theta}_g - F_{gy}R_g + (R_g\tan\alpha + H)F_{px} = -T_g \end{cases} \tag{2}$$

The meshing force between teeth includes elastic meshing force and viscous meshing force, so the dynamic meshing force acting on the gear is expressed as:

The longitudinal dynamic meshing force F_X is given by:

$$F_x = \lambda f F_y \tag{3}$$

where λ is directional coefficient of tooth friction. f is the equivalent friction coefficient.

The circumferential dynamic meshing force F_y is given by:

$$F_y = k_{py}(\overline{y}_p - \overline{y}_g - e_y) + c_{py}(\dot{\overline{y}}_p - \dot{\overline{y}}_g - \dot{\overline{e}}_y) \tag{4}$$

Axial dynamic meshing force F_z is given by:

$$F_z = k_{pz}(\overline{z}_p - \overline{z}_g - e_z) + c_{pz}(\dot{\overline{z}}_p - \dot{\overline{z}}_g - \dot{\overline{e}}_z) \tag{5}$$

Taking the pinion as an example, the relationship between the vibration displacement of point P and the generalized displacement is defined by:

$$\begin{cases} \overline{x}_p = x_p + \theta_p R_p \\ \overline{y}_p = y_p + \theta_p R_p \\ \overline{z}_p = z_p - \overline{y}_p \tan\beta \end{cases} \tag{6}$$

where R_P is the radius of the base circle of the driving pinion. β is helical angle of helical gear.

Translational vibration mesh stiffness, damping and meshing error are expressed as:

$$\begin{cases} k_{py} = k_m \cos\beta \quad k_{pz} = k_m \sin\beta \\ c_{py} = c_m \cos\beta \; c_{pz} = c_m \sin\beta \\ e_y = e\cos\beta \;\; e_z = e\sin\beta \end{cases} \tag{7}$$

where k_m, c_m, e are normal stiffness, normal damping and normal meshing error, respectively.

Therefore, the dynamic meshing forces in radial, circumferential and axial directions can be obtained:

$$F_{px} = \lambda f F_{py} \tag{8}$$

$$F_{py} = \cos\beta\left[k_m\left(y_p + \theta_p R_p - y_g - \theta_g R_g - e_y\right) + c_m(\dot{y}_p + \dot{\theta}_p R_p - \dot{y}_g - \dot{\theta}_g R_g - \dot{e}_y)\right] \tag{9}$$

$$\begin{aligned} F_{pz} &= \sin\beta\{k_m\left[z_p - z_g - \left(y_p + \theta_p R_p - y_g + \theta_g R_g\right)\tan\beta - e_z\right] \\ &+ c_m\left[\dot{z}_p - \dot{z}_g - \left(\dot{y}_p + \dot{\theta}_p R_p - \dot{y}_g + \dot{\theta}_g R_g\right)\tan\beta - \dot{e}_z\right]\} \end{aligned} \tag{10}$$

where m_i, I_i ($i = p,g$) are the mass and moment of inertia of the pinion and driven gears, respectively. α is the engagement angle. H is the distance from the meshing point to the node.

Based on the above analysis, the equation of torsional vibration degree of freedom of pinion can be expressed:

$$\begin{aligned} I_p\ddot{\theta}_p &= \left[\lambda f(R_p \tan\alpha - H) - R_p\right]\cdot\cos\beta\left[k_m(y_p + \theta_p R_p - y_g - \theta_g R_g - e_y) \right. \\ &\left. + c_m\left(\dot{y}_p + \dot{\theta}_p R_p - \dot{y}_g - \dot{\theta}_g R_g - \dot{e}_y\right)\right] - T_p \end{aligned} \tag{11}$$

The calculation formula of contact stiffness coefficient of gear is:

$$K = \frac{4}{3}R^{\frac{1}{2}}E \tag{12}$$

where R is the comprehensive radius of curvature, E is comprehensive elastic modulus.

It can be concluded from the formula that the variation of tooth surface COF and mesh stiffness will affect the torsional vibration response of helical gear. Therefore, the friction properties of manganese phosphate surface modified coating were tested to explore the effect of coating on gear vibration response.

3. Coating Characteristics

3.1. Coating Preparation

The surface particle size and coating thickness of manganese phosphate conversion coatings prepared by different phosphating processes are also different. Different thicknesses of manganese phosphate conversion coatings can be obtained by controlling the phosphating temperature and reaction time. Manganese phosphate conversion coating was prepared on the surface of standard friction samples by chemical conversion plating method according to the preparation process of reference [16]. Through the different phosphating reaction time and temperature, three kinds of the coating are prepared on the surface of standard friction samples φ24 mm × 7.9 mm which material is AISI 52100 alloy stell. Manganese phosphate conversion coatings disc specimens with different thicknesses are shown in Figure 2.

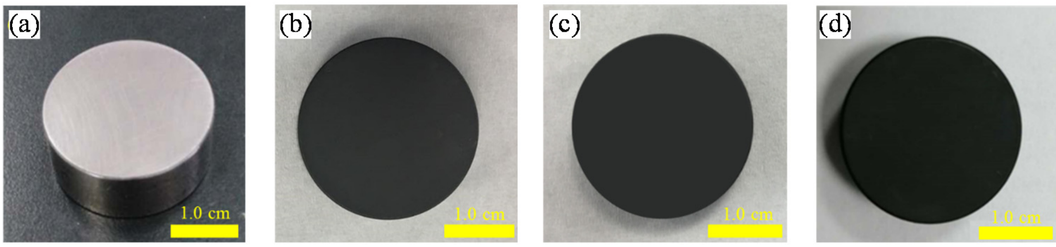

Figure 2. Manganese phosphate conversion coating samples with different thickness. (**a**) Uncoated, (**b**) Mn-P[A], (**c**) Mn-P[B], (**d**) Mn-P[C].

From the macro morphology of the coating, it can be seen that the color of manganese phosphate coating is gradually deepened with the increase in coating thickness. The density of the coating is an important parameter to characterize the thickness. The weight of the coating is measured by the weighing method [30], and the average density of the coating is obtained. The thickness of coatings is obtained through scanning electron microscopy [16]. The densities of three manganese phosphate conversion coatings with different thicknesses are shown in Table 1.

Table 1. Sample density of manganese phosphate conversion coating.

Sample	Coating Density (g/m^2)	Thickness (μm)	Label
Uncoated sample	0.0	-	Steel
Coating sample 1	2.5	3~5	Mn-P[A]
Coating sample 2	6.1	6~8	Mn-P[B]
Coating sample 3	10.5	12~15	Mn-P[C]

3.2. Elastic Modulus

In order to obtain the parameter properties of the coating material, the transmission gear material 20MnCrS5 was used as the base material, the same heat treatment process was adopted for the transmission gear, and the nano indentation instrument was used to test the surface elastic modulus of phosphating coating with different thickness. The data of pressure displacement curve is processed according to the method of reference [31].

In order to reduce the error of test data, six points on the coating surface were randomly selected for indentation test. Each experiment was repeated for five times. The loading time is 10 s and the duration is 15 s. Figure 3a shows the average nanoindentation depth curves and standard deviation of Mn-P[A], Mn-P[B] and Mn-P[C] coatings at 500 mN, respectively. The results show that the average indentation depths of Mn-P[A], Mn-P[B] and Mn-P[C] are 2170 nm, 3149 nm and 3794 nm, respectively.

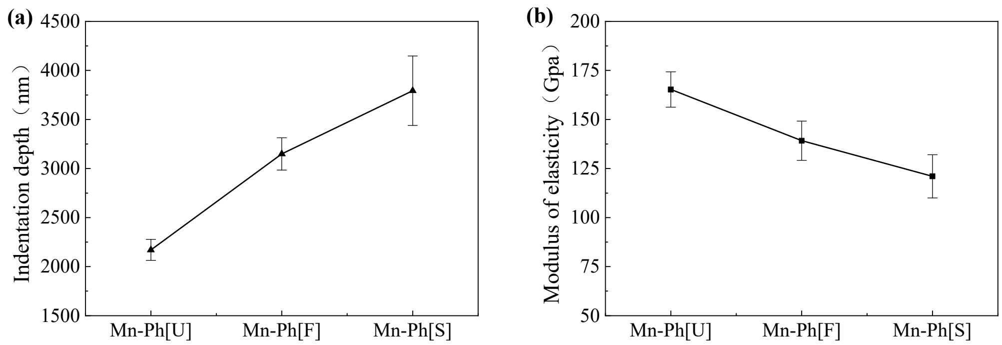

Figure 3. (**a**) The average nanoindentation depth; (**b**) The elastic modulus.

Based on the method established by Oliver, the elastic modulus of the coating was obtained according to the displacement curve. Figure 3b shows the elastic modulus of different coating thicknesses. With the increase in coating thickness, the elastic modulus decreases gradually. Mn-P[A] with smaller thickness has the largest elastic modulus, which is 165 Gpa. The elastic modulus of Mn-P[B] coating is 139 Gpa, and that of Mn-P[C] coating with maximum coating thickness is 121 Gpa.

3.3. Coefficient of Friction

In order to simulate the friction condition of manganese phosphate conversion coating in pure sliding contact of transmission system and obtain the COF under high load and pure sliding condition, the "ball-disk" point contact method was adopted. Then, the COF of different thickness coatings were obtained by Schwing–Reib–Verschleiß rig (SRV-V, Optimal Instruments, Munich, Germany) friction tester. During the test, the substrate material of upper and lower sample is AISI 52100 steel, which performs reciprocating sliding friction movement. The lower sample is three different thickness manganese phosphate conversion coating discs, which are in fixed state. The test parameters refer to ASTM D7421-11 [32]. SRV-V test conditions are shown in Table 2. The specific parameters and steps of SRV-V sliding friction test are detailed in reference [16]. When the normal load is 300 N, the variation curve of COF with the time of different thickness coatings are obtained. Each set of tests is performed three times and the average COF values are shown in Figure 4.

Table 2. Parameters of COF test.

Temperature (°C)	Load (N)	Pressure (GPa)	Oil Volume (mL)	Sliding Speed (m/s)	Stroke (mm)
80	300	3.1	0.3	0.1	2

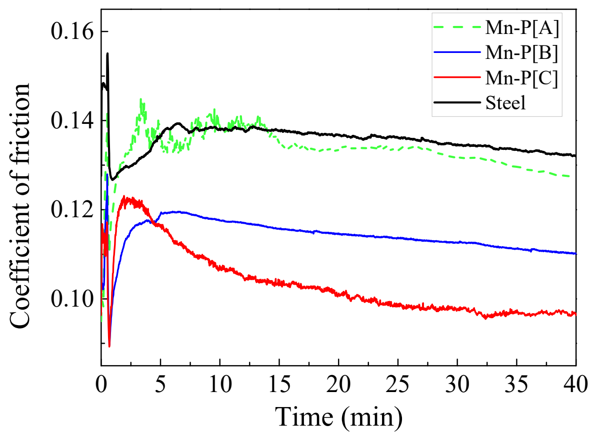

Figure 4. The curve of friction coefficient with different thickness coating.

It can be seen from the curve that the COF curve of Mn-P[A] sample fluctuates greatly at the initial stage. With the increase in test time, the COF shows a downward trend. After 35 min, the curve gradually flattens. The average sliding COF of the uncoated sample is between 0.131 and 0.142. In the steady stage, the COF of Mn-P[A], Mn-P[B] and Mn-P[C] are stable at 0.124, 0.107 and 0.096, respectively. Compared with the uncoated sample, the COF of the thick coating is the lowest, which is reduced by about 19%.

4. Performance of Gear Transmission

4.1. Gear Performance Test Bench

Through the previous theoretical analysis and coating characteristics test, the Mn-P[C] has a smaller elastic modulus and coefficient of friction. The solid lubrication coating can improve the tribological characteristics, reduce the coefficient of friction, and improve the gear transmission performance. According to the practical application support conditions of the first speed gear of the seven-speed dual-clutch transmission, a double motor gear transmission performance test bench was built, as is shown in Figure 5. The transmission performance of high concentration carbonitriding heat-treated 20MnCrS5 helical gear and thick-coated gear was evaluated. The influence of manganese phosphate conversion coating on the transmission performance of gears was analyzed.

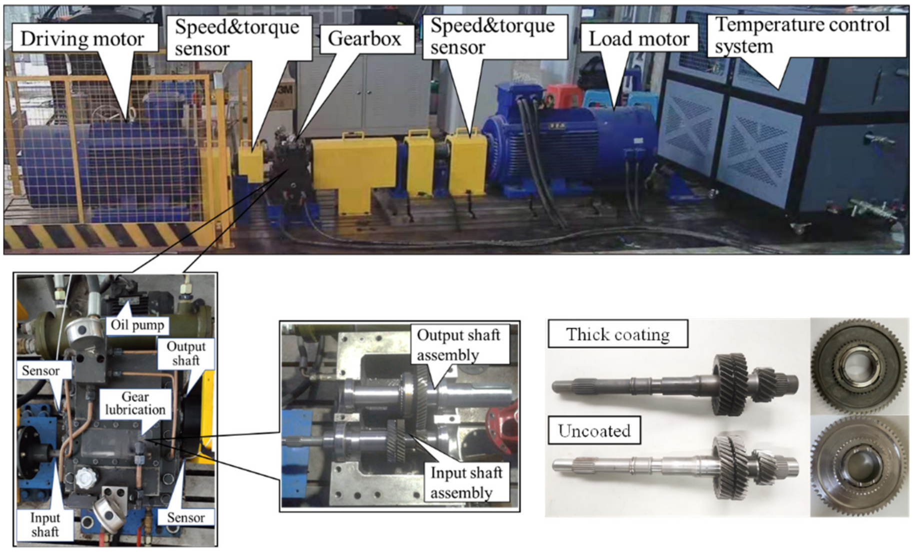

Figure 5. Gear transmission performance test bench.

The test bench consists of a driving motor, load motor, torque and speed sensors, gearbox, oil temperature control system and main console. There are two three-axis vibration acceleration sensors on the rear end cover of the input shaft and the front-end cover of the output shaft of the gearbox to monitor and collect the vibration data in real-time. In order to meet the requirements of the actual operation condition of the transmission gear, the technical parameters of the motor of the test bench are shown in Table 3. The test conditions are 2500 r/min and 240 N·m, oil injection lubrication and constant oil temperature of 80 °C. The uncoated and thick-coated gear pairs were installed, respectively. The dynamic characteristics of the gears were compared under the same operating environment.

Table 3. Technical parameters of motor.

Technical Parameter	Driving Motor	Load Motor
Rated speed (r/min)	3000	1000
Maximum speed (r/min)	6000	2000
Maximum torque (N·m)	420	1260
maximum power (Kw)	132	132

4.2. Running-In Characteristic

In order to verify the effect of coating on the surface properties of gear after running-in, the surface roughness *R*a and *R*q of uncoated and thick-coated pinion were measured through Tokyo precision SURFCOM NEX 001SD-12 instrument (Tokyo, Japan). Measure three different teeth are measured, and three times for each tooth surface. After two hours of stable running, the tooth surface roughness of two pairs of pinions was measured again. As shown in Figure 6, it shows the tooth surface roughness of uncoated and thick-coated gears before and after running-in.

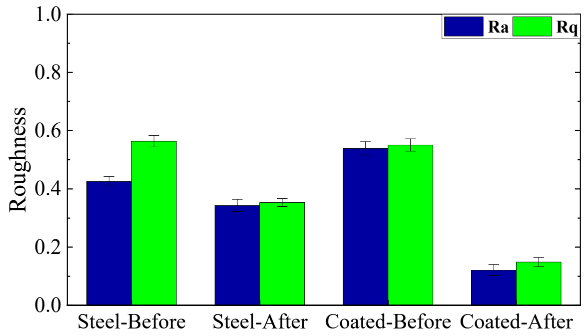

Figure 6. Roughness before and after running-in test.

Before running-in, the *R*a value of manganese phosphate conversion thick coating is 26.5% higher than that of uncoated gear, and the Rq value is basically the same. The results show that the manganese phosphate conversion coating can increase the gear tooth surface roughness. After running-in, the tooth surface roughness of the two gears decreased. The roughness Ra of uncoated gear decreased by 19.5% to 0.343 μm. Rq decreased by 37.4% to 0.353 μm. However, after running-in, the roughness of the thick coated gear decreases by 77.6%, with an average of 0.121 μm. Rq decreased 73.0% to 0.149 μm. The results indicate that the tooth surface roughness of the two pairs of gears is improved and becomes smoother after running-in. After running-in, the tooth surface roughness of the gear with thick coating is 35.3%~42.2% of that of the gear without coating. As shown in Figure 3a, with the increase in the thickness of manganese phosphate conversion coating, the nanoindentation depth increases. It indicates that the manganese phosphate conversion coating belongs to soft coating. The initial roughness of the gear increases after coating. However, after running-in, the initial roughness is removed and the tooth surface roughness decreases obviously.

4.3. Transmission Efficiency

The factors that affect gear transmission efficiency include gear accuracy, lubricating oil properties, bearing clearance, machining error, assembly error and so on. The gearbox is tested by adopting the same type of lubricating oil and bearing, installed according to the same assembly requirements. The transmission efficiency is obtained under the same and stable lubricating oil temperature. The speed of the driving motor is 2500 r/min, and the torque of the load motor is 240 N·m. Through the bench torque and speed sensors, the speed and torque data of the input and output end of the transmission gear are collected, respectively. The transmission efficiency of the gear pair is calculated according to the following formula:

$$\begin{cases} P_{in} = \frac{2\pi T_{in} n_{in}}{60} \\ P_{out} = \frac{2\pi T_{out} n_{out}}{60} \\ \eta = \frac{P_{in}}{P_{out}} \times 100\% \end{cases} \tag{13}$$

where T_{in} and T_{out} are the torque of driving motor and load motor, respectively. n_{in} and n_{out} are the speed of driving motor and load motor, respectively.

The data acquisition frequency of the speed and torque is 1 Hz, and the transmission efficiency is calculated for 30 s continuously when the running condition is stable. As shown in Figure 7, the average transmission efficiency of the thick-coated gear pair is 98.28%, which is 0.58% higher than that of the uncoated gear pair.

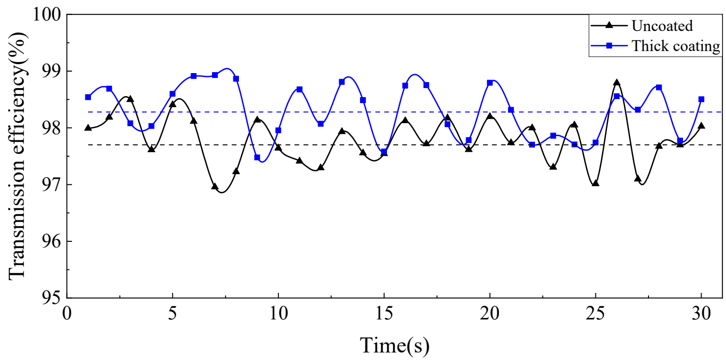

Figure 7. Comparison of gear transmission efficiency.

4.4. Vibration Characteristics

After the gear running-in, the vibration acceleration signals at the input and output ends are collected under the same working conditions. Sensor 1 is attached to the input end bearing cover, and sensor 2 is attached to the output end bearing cover. The sampling frequency is 12,000 Hz, and the data is collected for two seconds at an interval of two minutes, which makeup a group. In total, 8640 data points are taken for each group of data, and 20 groups of data are taken for comparative analysis of average vibration amplitude $\overline{X}$ and root mean square value X_{rms}.

As shown in Figure 8, the average amplitude and standard deviation of vibration acceleration of 6 channels are shown, and the calculation formula is as follows:

$$\overline{X} = \frac{1}{n} \sum_{i}^{n} |x_i| \tag{14}$$

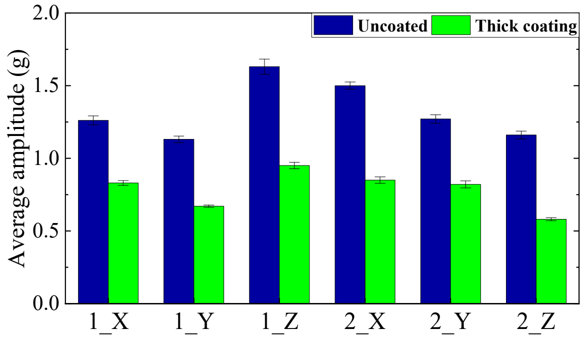

Figure 8. Average amplitude and standard deviation of vibration acceleration.

The average vibration amplitude of uncoated gear is 1.12 g~1.63 g, and that of thick coated gear is 0.58 g~0.95 g. The vibration amplitude of uncoated gear is higher than that of thick coated gear. Compared with uncoated gear, the average amplitude of the input end decreases by 34.29%, 40.56% and 41.55% in the X, Y and Z directions, respectively. The average amplitude of the output end is reduced by 43.35%, 35.17% and 49.77%, respectively. In the axial direction, the reduction in vibration amplitude is the most obvious.

The root mean square value is used to characterize the signal energy, which is expressed as the following:

$$X_{rms} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} {x_i}^2} \tag{15}$$

The root mean square value of 6 channels of gear vibration signal is processed, and the results are shown in Figure 9. The root mean square amplitude of uncoated gear is in the range of 1.63 g~2.34 g, while the root mean square amplitude of the thick coated gear is in the range of 0.88 g~1.47 g. In the X, Y and Z directions, the input end decreases by 35.49%, 41.29% and 37.1%, respectively. The output end decreases by 40.44%, 33.03% and 42.65%, respectively.

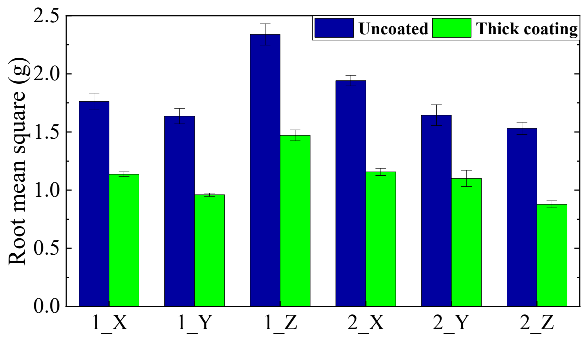

Figure 9. Root mean square value and standard deviation of vibration acceleration.

From the above helical gear dynamic model, it can be seen that the coefficient of friction and mesh stiffness have an influence on the torsional vibration response. After the helical gear tooth surface is treated with manganese phosphate conversion coating, due to the property of soft coating, the tooth surface roughness and coefficient of friction are reduced. On the other hand, the elastic modulus of coated gear is greatly reduced, resulting in the reduction in gear mesh stiffness and damping. According to the conclusion of reference [4], the elastic modulus is reduced, the dynamic meshing force is increased, and the torsional angle vibration acceleration amplitude is reduced in combination with the torsional dynamic equation.

5. Conclusions

In this paper, the 8-DOF dynamic equation of helical gear considering friction factor is established. The effect of the coating elastic modulus and COF on the dynamic response is investigated. Through the sample test of manganese phosphate conversion coating, the tribological properties of the coating are obtained. The gear transmission performance is present through the bench test of the coated gear. The following conclusions are obtained.

1. Manganese phosphate conversion coating can reduce the elastic modulus of materials. By comparing three kinds of coating samples with different thicknesses, the elastic modulu of Mn-P[C] sample is the least.
2. Through the SRV-V friction tester, the COF tends to decrease with the thickness of the coating, and the COF of the thick coating decreases by 19%. After running-in, the tooth surface of the coated gear become smoother and the roughness decreases obviously.
3. The amplitude of average vibration acceleration and root mean square value of gear with thick manganese phosphate conversion coating are reduced significantly. Moreover, the transmission efficiency is improved by 0.58%. The coating is beneficial to gear transmission performance.

Author Contributions: Conceptualization, Y.C. and L.Z.; methodology, G.L. and L.Z.; software, G.L.; validation, G.L., Y.T. and R.L.; formal analysis, G.L.; investigation, G.L.; resources, Y.C.; Y.T.; data curation, G.L. and R.L.; writing—original draft preparation, G.L.; writing—review and editing, Y.C., Y.W. and D.J.; visualization, G.L.; supervision, Y.W.; project administration, Y.C.; funding acquisition, Y.W. and Y.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Key R&D Program of China (NO. 2018YFE0207000).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The gear data set supplied by Yong Chen under license and so cannot be made freely available. Requests for access to these data should be made to the author.

Conflicts of Interest: The authors declare no conflict of interest.

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