International Research Journal of Advanced Engineering and Science
ISSN (Online): 2455-9024

Research on the Influence of Dynamic Factors on Planetary Gear Wear After Surface Heat Thermochemical Treatment

Hoang Van Thu
MTV-179 Mechanical Company, Hanoi, Vietnam
Email address: hoangthu179@gmail.com

Abstract**—***This article presents the research results of the dynamic parameters influence on the wear of planetary gears surface heat thermochemical treatment. These dynamic parameters include contact stress and tangential velocity while gears are subjected to heavy loads. The surface heat treatment steps include carbon infiltration and plasma nitriding. Tests to evaluate the wear of planetary gears were performed on two sample materials including C45 steel - TCVN and 20ХГМ steel - GOST. Regression equations are built on the basis of the two-factor Box-Wilson model. The research results can be used as a basis to determine the reliability and longevity of planetary gears in transmission systems subjected to heavy loads.*

Keywords**—***Planetary gears, wear, stress, velocity, thermochemical treatment.*

I. INTRODUCTION

Planetary gear transmission is one of the main parts of automatic transmissions on cars. Automatic transmissions with multiple gears can be created by combining two or more planetary transmissions together. The front and rear planetary gear units are connected to the clutches and brakes. These gears switch the positions of the primary and fixed elements to produce different gear ratios. Thus, planetary gears play an important role in creating many different speed levels of the car. Accordingly, ensuring the working ability of these planetary gear sets is very necessary.

Among the types of gear failures, tooth wear is the most common factor but is difficult to determine accurately. Especially for planetary gear systems when it continuously moves compared to gears with fixed shafts. There have been many studies on the problem of planetary gear wear such as [1-15]. The damage state and wear development of planetary gear transmissions have been considered in [1] based on vibration analysis techniques. Similarly, vibration modeling and error development analysis of planetary gear system to evaluate wear condition are also presented in [2]. A dynamic model of planetary gear transmission that includes tooth wear is introduced in [3] to monitor and predict the working condition of the gear. The planetary gear wear mechanism is also considered in [4] based on the construction of a hardness model combined with the three-segment tooth profile equation. The tooth surface wear probability of planetary gears is calculated in [5] based on experimental techniques and data statistics. The probability distribution is performed on the Weibull model. A method for predicting gear wear under dynamic dynamic conditions is proposed in [6]. Accordingly, the prediction method generates a model that can evaluate the interaction between surface wear and dynamic behavior in both linear and nonlinear response regimes. Similarly, a tooth surface wear prediction model based on dynamic conditions and assessment of wear accumulation and load sharing is also considered in [7]. The influence of reaction forces generated by accumulated tooth wear on the dynamic behavior of compound planetary gear sets is studied in [8]. Reliability varies with drive time and the optimized design of planetary reducers considering gear wear is considered in [9]. Dynamic wear analysis techniques are considered in [10] to evaluate the life and performance of planetary gears. The effects of wear and operating temperature of planetary gears are considered in [11] to build a model to analyze their nonlinear dynamic characteristics.

Among the factors causing tooth wear, contact stress and tangential velocity on the teeth are also the main influencing factors. Research [12] has built a loaded tooth contact analysis model to determine the relative sliding velocity and contact stress. From there, gear wear is calculated in a simple engagement cycle and the effects of changing tooth profiles and dynamic impact conditions during work can be evaluated. The contact stress and relative sliding distance between discontinuous tooth surfaces were calculated in [13] to build a tooth wear prediction model. Similarly, tooth wear was also predicted in [14] based on determining contact stress through finite element modeling and Archard's formula. Yuksel in [15] calculated the dynamic contact stress in a quasi-static planetary gear set and the Archard formula was used to determine the wear.

This article focuses on building a planetary gear wear prediction model and evaluating the influence of factors including contact stress and tangential velocity for two steel samples. Accordingly, these steel samples passed heat treated and surface treated using thermochemical techniques. Research results can be used for practical applications to evaluate the lifespan and working ability of gears with corresponding materials. Research content is distributed in specific sections. First, section 2.1 presents the experimental problem with the corresponding objectives and experimental system. Next, section 2.2 describes the experimental results and the results of building regression equations based on the Box-Wilson model. Finally, section 2.3 presents assessments of the influence of contact stress and tangential velocity on planetary gear wear.

II. MATERIALS AND METHODS

A. Experimental Setting

The goal of the experiments was to build a planetary gear wear regression model based on measured factors including contact stress and tangential velocity. Wear test samples include C45 steel and 20XГM steel that have been heat-treated and surface heat thermochemical treatment. Images of gears are shown in Fig. 1.

Fig. 1. Experimented gear samples

The material composition of the measured samples is described in Tab. 1.

TABLE I. CHEMICAL COMPOSITION OF EXPERIMENTAL SAMPLES

Steel	Chemical composition (%)							
	C	Mn	P	S	Si	Cr	Ni	Mo
C45	0.43	0.68	0.02	0.03	0.21	0.21	0.24	0.03
20XГM	0.23	0.71	0.02	0.03	0.19	0.96	0.19	0.23

The main parameters in the Plasma nitriding process are described in Tab. 2.

TABLE II. TECHNOLOGICAL PARAMETERS OF PLASMA NITRIDING

No	Steel	Voltage (V)	Time (h)	T(°C)	Scale H_2:N_2	Presure (Pa)
1	C45	470	8	540	1:3	250
2	20XГM	470	8	540	1:3	250

The hardness of the samples before and after surface treatment is shown in Tab. 3.

TABLE III. HARDNESS VALUES OF TESTED SAMPLES

Material	20XГM steel		C45 Steel	
SHTT	Carburized	Plasma nitriding	Carburized	Plasma nitriding
Hardness (HRC)	59.6	62.3	54.3	56.2

The process diagram for preparing material samples is depicted in Fig. 2.

After grinding, the gear sample is tested for surface roughness on a Mitutoyo SJ-400 tester with a value of Ra=0.63 µm. After being carburized and plasma nitriding, the gear is measured and determine the normal length of the gear, face runout and axial distance between the gears. The wear test diagram is depicted in Fig. 3. The planetary gear set tested in practice is depicted in Fig. 4.

The input variables of the test problem include: tangential velocity $V(m/s)$ and contact stress $s_H(MPa)$. Determining the range of input variables must ensure that the following criteria are met: the tangential velocity must ensure the occurrence of wear, and the contact stress must be less than the allowable stress value. The amount of wear $U(mm)$ is determined based on the measurement of the common normal length as follows

$$U = L_{st} - L_{dm} \quad (1)$$

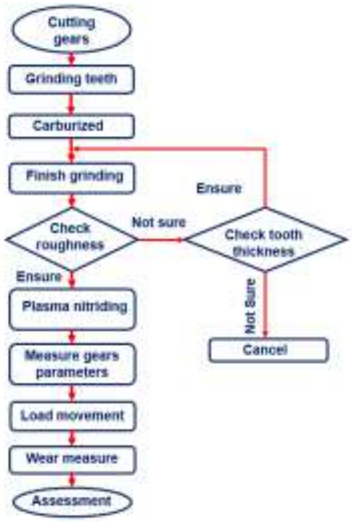
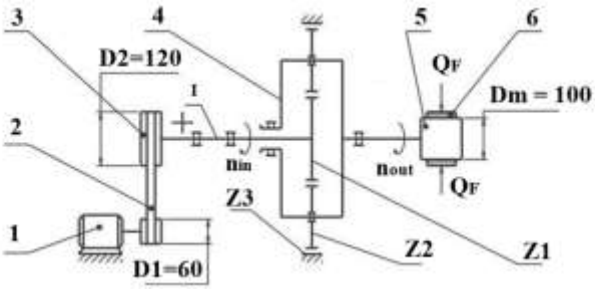


Fig. 2. Preparing and performing process experiments with material samples



(1) motor; (2) Belt transmission; (3) Puly; (4) Shelf; (5) Friction wheel; (6) Brake pads

Fig. 3. Wear test diagram

Fig. 4. Actual wear test model

In which, $L_{st}(mm)$ is the common normal length after plasma nitriding, and $L_{dm}(mm)$ is the common normal length at the time of measurement during the load test. The regression model used is the Box-Wilson model with two input factors and is described in detail in [16]. The range and rating of the input parameters are shown in Tab. 4.

TABLE IV. INPUT VARIABLE LEVELS

No	Variables	Level 1	Level 2	Level 3
1	$V\,(m/s)$	0.95	1.25	1.55
2	$s_H\,(MPa)$	100	200	300

The number of experiments for each material is 9. The wear test time is determined according to the load run time with 1000h. There are 2 shifts per day and each shift is 5 hours.

B. Experimetal results

Test results with C45 steel material sample after Plasma Nitriding are shown in Tab. 5.

TABLE V. EXPERIMENTAL RESULTS AND WEAR PREDICTION WITH C45 STEEL SAMPLE

No	$s_H(MPa)$	$V\,(m/s)$	$U_{real}(mm)$	$U_{Predict}(mm)$	$Error(\%)$
1	100	0.95	0,045	0,0425	5.56
2	300	0.95	0,080	0,0699	12.62
3	100	1.55	0,145	0,1341	7.51
4	300	1.55	0,225	0,2208	1.87
5	200	1.25	0,100	0,1108	10.8
6	300	1.25	0,135	0,1332	1.33
7	100	1.25	0,075	0,0809	1.97
8	200	1.55	0,175	0,1837	4.97
9	200	0.95	0,055	0,0582	5.82

The regression equation establishing the relationship between the amount of gear wear after plasma nitriding with the contact stress and tangential velocity for the C45 steel sample is determined as follows

$$U = 0.003401 s_H^{0.5904} V^{2.489} (mm) \quad (2)$$

Tab. 6 presents the test results and prediction of wear after plasma nitriding with 20XГM steel sample.

TABLE VI. EXPERIMENTAL RESULTS AND WEAR PREDICTION WITH 20XГM STEEL SAMPLE

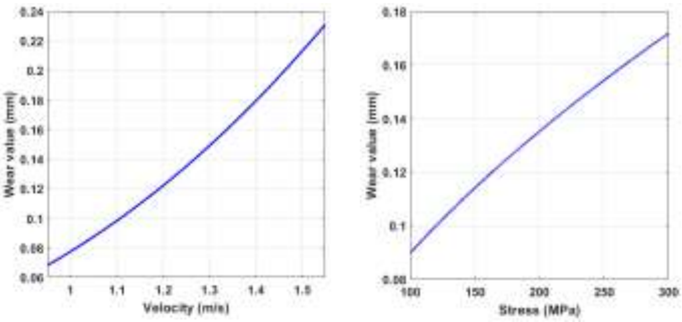
No	$s_H(MPa)$	$V\,(m/s)$	$U_{real}(mm)$	$U_{Predict}(mm)$	$Error(\%)$
1	100	0.95	0,035	0,0286	18.28
2	300	0.95	0,060	0,0492	18.0
3	100	1.55	0,100	0,0952	4.8
4	300	1.55	0,170	0,1635	3.82
5	200	1.25	0,065	0,0790	21.53
6	300	1.25	0,090	0,0964	7.11
7	100	1.25	0,055	0,0562	2.18
8	200	1.55	0,130	0,1339	3.0
9	200	0.95	0,042	0,0403	3.78

The regression equation establishing the relationship between the amount of gear wear after plasma nitriding with the contact stress and tangential velocity for the 20XГM steel sample is determined as follows

$$U = 0.003368 s_H^{0.4921} V^{2.454} (mm) \quad (3)$$

C. Discussions

Based on the limited value of input variables including $100(MPa) \le s_H \le 300(MPa)$ and $0.95(m/s) \le V \le 1.55(m/s)$, the influence of these parameters on gear wear value is specifically considered. Fig. 5 describes the influence of each input parameter on the amount of gear wear of C45 steel material. Accordingly, if $s_H = 200(MPa)$, the amount of wear depends on the speed according to Fig. 5a. Accordingly, the maximum wear value when the speed increases is 0.23 (mm). On the contrary, if the velocity is $V = 1.25(\frac{m}{s})$, the contact stress affects the amount of wear as shown in Fig. 5b. Accordingly, the maximum wear value can reach 0.172 (mm). This shows that, if the contact stress parameter is fixed, the tangential velocity causes greater wear.

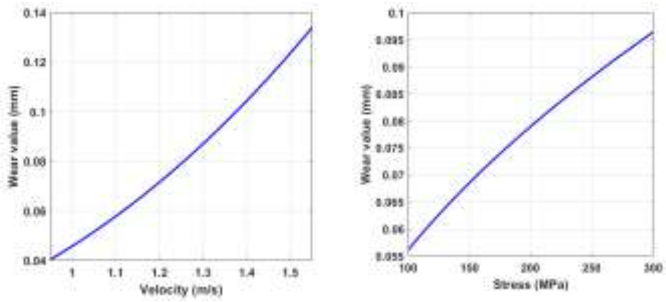


(a) Effect of V while $s_H = 200(MPa)$

(b) Effect of s_H while V=1.25 (m/s)

Fig. 5. Effect of each input factor on C45 steel sample

Fig. 6 describes the influence of each input parameter on the amount of gear wear of 20XГM steel material.



(a) Effect of V while $s_H = 200(MPa)$

(b) Effect of s_H while V=1.25 (m/s)

Fig. 6. Figure 6. Effect of each input factor on 20XГM steel sample

Similar analysis for material sample C45. Obviously, the contact stress factor has less influence on the amount of gear wear than the tangential velocity value if the influence of each fixed parameter is evaluated. If $s_H = 200(MPa)$, then the amount of wear depends on the velocity according to Figure 6a. The maximum wear value when the speed increases to 1.55 (m/s) is 0.133 (mm). On the contrary, if the velocity is $V = 1.25(m/s)$, the contact stress affects the amount of wear as shown in Figure 6b. The maximum wear value can reach 0.172 (mm).

Fig. 7 and Fig. 8 depict the simultaneous influence of input factors on the corresponding steel samples.

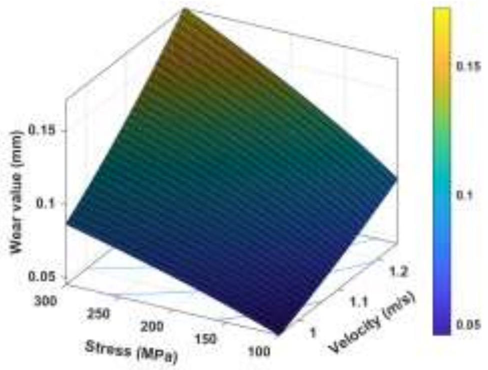


Fig. 7. Wear amount of C45 steel sample with two influencing factors

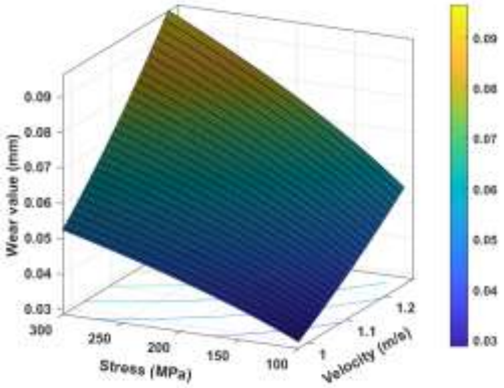


Fig. 8. Wear amount of 20XГM steel sample with two influencing factors

It is easy to see the similarity in shape of the two graphs in Fig. 7 and Fig. 8. The wear value of planetary gears will increase when increasing the value of velocity and contact stress. Increasing the contact stress will increase the amount of wear faster than increasing the tangential velocity in both cases. The maximum wear value of the gear with C45 steel material (0.171mm) is much higher than that of 20XГM material (0.096 mm) under the same testing conditions. Based on the results of impact analysis, it can be seen that in fact increasing the input variable values increases gear wear, leading to reduced gear life and working ability. However, when it is necessary to increase input variable values to match actual working conditions, the tangential velocity should be increased first, limiting the increase in contact stress. This means that gear manufacturing needs to be more precise in terms of technical specifications such as dimensional accuracy, face runout, tooth profile accuracy and surface permeation layer thickness. It should be noted that the results of analyzing the influence of each fixed parameter do not have any contradictions with the above analysis results. This is easy to explain because it is difficult to fix the input variable parameters and the results of evaluating the simultaneous influence of many factors are more valuable and closer to reality, showing more clearly the nature of nonlinar of regression models.

III. CONCLUSIONS

In general, the article has presented the results of building regression models to determine the relationship between the amount of wear of planetary gears and changing factors including contact stress and tangential velocity. C45 steel and 20XГM steel samples were used to perform the experiments. These steel samples are surface heat thermochemical treatment . The results of evaluating the influence of the factors show that the wear value will increase rapidly when simultaneously increasing the value of the input variables. In particular, contact stress has a greater influence on wear value than tangential velocity if the influence of these factors is considered simultaneously. On the contrary, if a variable value is fixed, the tangential velocity causing wear is larger than the contact stress. This research result has important value in formulating practical problems associated with specific tasks.

REFERENCES

[1] W. C. Zhao, H. Zhuang, Z. Yang, Deterioration State Diagnosis and Wear Evolution Evaluation of Planetary Gearbox Using Vibration and Wear Debris Analysis, Measurement 193(7):110978, 2022.

[2] X. Liu, Vibration modelling and fault evolution symptom analysis of a planetary gear train for sun gear wear status assessment, Mechanical Systems and Signal Processing 166(7):108403, 2022.

[3] M. Gao, Z. Shang, W. Li, et al. Analysis of Wear Mechanism and Fault Characteristics of Planet Gears with Multiple Wear Types in Planetary Gearbox. J. Vib. Eng. Technol. 11, 945–975 (2023). https://doi.org/10.1007/s42417-022-00618-5

[4] P. Zivkovic, M. Ognjanovic, et al, Assessment of Probability of Gear Tooth Side Wear of a Planetary Gearbox, Technical Gazette 27, 2, 506-512, 2020.

[5] A. Kahraman, H. Ding, A Methodology to Predict Surface Wear of Planetary Gears Under Dynamic Conditions, Mechanics Based Design of Structures and Machines, 38(4):493-515, 2010.

[6] H. Zhang, S. Shen, A dynamic tooth wear prediction model for reflecting "two-sides" coupling relation between tooth wear accumulation and load sharing behavior in compound planetary gear set, ARCHIVE Proceedings of the Institution of Mechanical Engineers Part C Journal of Mechanical Engineering, 234(9):095440621990008, 2020.

[7] S. Wu, H. Zhang, et al, Influence of the backlash generated by tooth accumulated wear on dynamic behavior of compound planetary gear set, ARCHIVE Proceedings of the Institution of Mechanical Engineers Part C Journal of Mechanical Engineering, 231(11), 2016. DOI: 10.1177/0954406215627831

[8] B. Pan, C. Lin, Y. Xiang, et al, Transmission time-variant reliability analysis and optimization design of planetary reducers considering gear wear, Jisuanji Jicheng Zhizao Xitong/Computer Integrated Manufacturing Systems, CIMS 28(3):745-757, 2022.

[9] J. Wang, J. Zhang, Assessment of Residual Useful Life of Sun Gear in a Planetary Gearbox Based on Dynamic Wear Behaviors Analyses, Machines, 11, 149, 2023.

[10] Z. Shena, B. Qiaoa, L. Yanga, et al, Dynamic modeling of planetary gear set with tooth surface wear, Procedia Manufacturing 49, 49–54, 2020.

[11] J. Wang, X. Bi, Z. Luo, et al, Analysis of nonlinear dynamic characteristics of planetary gears considering the in§uence of wear and temperature effects, 11 December 2023, PREPRINT (Version 1) available at Research Square [https://doi.org/10.21203/rs.3.rs-3374326/v1].

[12] X. Li, L. Haidong, Y. Weilong, et al, Investigation on Tooth Surface Wear of Cycloid Drives Considering Tooth Profile Modifications, Lubricants 11(8):323, 2023.

[13] A. Flodin, S. Andersson, Simulation of mild wear in spur gears. Wear, 207, 16–23, 1997.

[14] D. Park, A. Kahraman, A surface wear model for hypoid gear pairs, Wear, 267, 1595–1604, 2009.

[15] C. Yuksel, A. Kahraman, Dynamic tooth loads of planetary gear sets having tooth profile wear. Mech. Mach. Theory, 39, 695–715, 2004.

[16] Sönmez, K. Şahbudak, Optimization of sponge iron (direct reduced iron) production with Box-Wilson experimental design by using iron pellets and lignite as reductant, Revista de Metalurgia 59(2):e241, 2023. DOI: 10.3989/revmetalm.241.