www.dergipark.gov.tr
ISSN:2148-3736
El-Cezerî Fen ve Mühendislik Dergisi
Cilt: 8, No: 1, 2021 (495-503)

El-Cezerî Journal of Science and Engineering
Vol: 8, No: 1, 2021 (495-503)
DOI:10.31202/ecjse.828444

ECJSE

Research Paper / Makale

Effect of the Operating Temperature of Oil on Gear Teeth Surface Damages

İbrahim YAVUZ[1a*], İbrahim MUTLU[1b], Ahmet ÇETKIN[2c], Bahadır İŞEL[3d]

[1]Afyon Kocatepe University, Faculty of Technology, Department of Automotive Engineering, Afyon/Turkey
[2]Afyon Kocatepe University, Faculty of Technology, Department of Mechanical Engineering, Afyon/Turkey
[3]Afyon Kocatepe University, Institute of Science, Afyon/Turkey
iyavuz@aku.edu.tr

Received/Geliş: 19.11.2020 **Accepted/Kabul:** 21.01.2020

Abstract: Gears are widely used in motion transmission in machines. For this reason, they work in very difficult conditions. Some damage may occur in the gears depending on the operating conditions. These damages are bending fatigue, pitting, micropitting, scuffing, and wear. This study investigates surface fatigue damages by keeping fixed the material of test gear teeth, rotation speed, lubricating oil, and the applied load, and changing the operating temperatures of oil. In experimental studies, pre- and post-test weights of gear teeth samples were established, surface roughnesses were measured, and micrograph examinations were carried out on teeth surface. As a result, surface roughness and wear were established to increase in proportion to the rise in temperature of oil. Maximum pitting size was measured at about 870 μm at 90 ºC oil temperature, and the lowest pitting size was measured as approximately 450 μm in tests performed at 30 ºC.

Keywords : Gear fatigue, Oil temperature, Oil viscosity, Spur gear

Yağ Çalışma Sıcaklığının Dişli Yüzey Hasarları Üzerine Etkisi

Öz: Dişliler hareket iletiminde makinalarda oldukça yaygın olarak kullanılmaktadır. Bu sebeple oldukça güç şartlarda çalışmaktadırlar. Çalışma şartlarına bağlı olarak dişlilerde bazı hasarlar meydana gelirt. Bu hasarlar eğilme yorulması, pitting, mikropitting, sürtünme ve aşınmadır. Bu çalışmada test dişlilerinin malzemesi, devir sayısı, yağlama yağı ve uygulanan yük sabit tutulmuş olup yağ çalışma sıcaklıkları değiştirilerek yüzey yorulma hasarları incelenmiştir. Deneysel çalışmalarda dişli numunelerinin deney öncesi ve sonrası ağırlıkları tespit edilmiş, yüzey pürüzlülükleri ölçülmüş, dişli yüzeylerinde mikrograf incelemeleri yapılmıştır. Sonuç olarak sıcaklığın artması ile doğru orantılı olarak yüzey pürüzlülüğünün ve aşınmanın da arttığı tespit edilmiştir. Maksimum pitting boyutu yaklaşık 870 μm ile 90 ºC'deki yağ sıcaklığında ölçülmüş olup en düşük pitting boyutu ise 30 ºC'de yapılan testlerde yaklaşık 450 μm olarak ölçülmüştür.

Anahtar Kelimeler: Dişli yorulması, Yağ sıcaklığı, Yağ viskozitesi, Düz dişli

1. Introduction

Gear wheel is the most widely used mechanism among power- and rotation-conveying elements and is comprised of at least two gear teeth. Gear wheels are quite common in almost all fields of life parallel to technologic advancements.

Gear wheels are machinery elements that operate under various environments and conditions and that take up a significant place in the industry. Therefore, it is a necessity to know about the damage

How to cite this article
Yavuz İ., Mutlu İ., Çetkin A. İşel B., "*Effect of the operating temperature of oil on gear teeth surface damages"*, El-Cezerî Journal of Science and Engineering, 2021, 8(1); 495-503.

Bu makaleye atıf yapmak için
Yavuz İ., Mutlu İ., Çetkin A. İşel B., "*Effect of the operating temperature of oil on gear teeth surface damages"*, El-Cezerî Fen ve Mühendislik Dergisi 2021, 8(1); 495-503.
ORCID ID :[a]0000-0002-4480-2342; [b]0000-0001-5563-1000; [c]0000-0003-4592-5632; [d]0000-0003-2667-4823

occurring on this important element and to establish their causes. For this reason, the results of pressure, wear, crack, and surface fatigue experiments conducted with disks manufactured from various materials and bearing different characteristics were adapted to gear wheels by establishing geometric similarity [1].

Tribology is defined as the science of friction, branching and lubrication of the interacting relative moving surfaces. Wear is a major problem in the industry, reducing the efficiency of the machines [2].

Surface damages and pitting formation processes occurring on gear wheels constituted the subject matter of numerous experimental and theoretical studies since 1930s, and these damages began to be studied by more scientific methods [1]. On gear wheels that operate by coming into contact with each other, heat is produced as a result of friction. Viscosity of lubricating oil changes due to the effect of heat, and wear, noise, and vibration occur as a result. A plethora of studies and experiments are carried out on wear occurring on gear wheels.

Some of these studies are as follows: gear wear fault mechanism, most conventional researches mainly concentrated on the evaluation of gear wear [3-9], and the effect of gear wear on tooth profile [10], transmission errors [11,12] and mesh stiffness [13-16]. According to the mechanism of wear fault, dynamic study of tooth wear mainly focused on dynamic responses [14, 17, 18], and nonlinear dynamics [19]. The following is a detailed introduction of fault mechanism and dynamic analysis.

Padgornik and Vižintin used in their studies gear wheels nitrided by plasma and impulse plasma and manufactured from 42CrMo4 steel. They studied wear resistance and pitting formation process of these gear wheels under lubricated sliding conditions. Based on the test results, they established that wear and pitting formation of gears nitrided with plasma and impulse plasma reduced greatly compared to spur gear [20]. In their study, Yavuz et al. different oil viscosities on gear wheels are investigated. They studied to the results of the surface roughness tests, as the oil viscosity decreases, the surface roughness and material loss increase [21].

Dempsey tried to establish in a study the gear damage by examining oil contamination. Dempsey determined oil contamination with a sensor and noted that the increase in oil contamination was directly related to pitting formation. Based on the contaminating grain amount in oil, he established the formation stages of pitting damage occurring on gear surface and the limits distinguishing such stages [22]. Meshari et al. suggested that breaks on the gear resulted from excessive pitting on gear surfaces. They also suggested that the factor increasing the pitting formation might stem from insufficient lubrication system or the use of wrong oil [23]. Fontanari et al. studied tribological behaviors of a gear wheel pair manufactured from bronze (CuSn12)-steel (42CrMo4V) gears. They established that damage formation was lower in gear wheel made from steel compared to bronze gear. They also observed deep scratches and pitting formation on bronze gear wheel [24].

Among the fundamental elements in the use of gear wheel, lubricants generally operate under severe conditions. Not yet adequately accounted for despite numerous studies until today, lubricants and the effects of operating temperatures on the formation of wear types are important. For this reason, this study investigates the effect of oil temperature on gear wheel fatigue.

2. Experimental Methods

In the experiments, the material of the test gear, number of cycles, temperature (30°C-60°C-90°C), and applied load were kept constant, while lubricants having different viscosities were used. The test samples underwent five million cycles, from which the scanning electron microscope images and the values of surface roughness and wear were investigated.

2.1. Gear Fatigue Test Device

In gear fatigue experiments, closed-circuit gear fatigue devices are generally used. In these types of devices, the loading is done by mechanical weight. These experiments used the gear fatigue test apparatus of the department of Mechanical Education at Afyon Kocatepe University. In the device used, loading was done with electricity instead of mechanical weights; a schematic view of the device is given in Figure1.

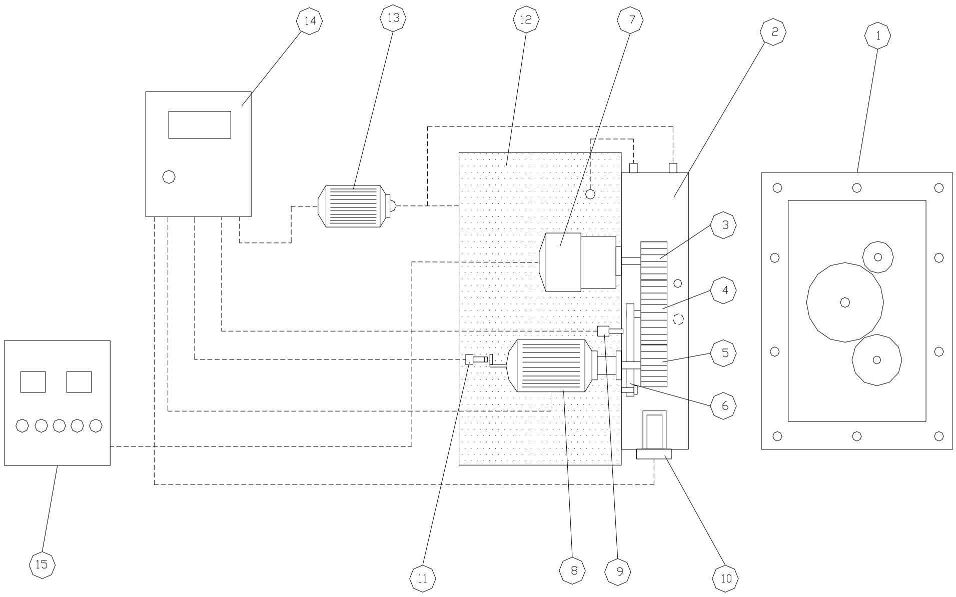

Figure 1. Schematic view of the device. 1,2-Test Gear Box, 3- Test Gear, 4- Mediocre Gear (Moving), 5 Pinion (Hard), 6-, 7- Paraçol Generator (Resistance Board) 8. Electric Motor, 9 Temperature Sensor, 10 - Oil Heater (Resistance), 11 Reading Speed Sensor, 12 Water tanks, 13 Water Pump, Control Panel 14-, 15- Panel İnstallation

The gear wear experiment device receives its stimulus from an electric motor. At the end of the electric motor shaft there is a turning gear. This turning gear rotates the intermediate idler gear, and the intermediate gear rotates the test gear. The test gear is attached to the alternator shaft. Through this mechanism, the experimental device rotates the alternator by the stimulus it receives from the electric motor, and the alternator produces electricity. The generated electricity is depleted with a heating device. Because the test gear is attached to the end of the alternator, the test gears are loaded during the depletion of the electricity. The manufactured gear test device is shown in Figure 2.

Figure 2. Gear appearance of fatigue test device

In order to adjust the temperature parameter in the gear experiments, a heating and cooling mechanism to adjust the temperature was installed on the experimental device. In order to reduce the temperature, a 55-litre water tank was put under the gearbox. In order to prevent rinsing and to provide water for cooling, a perforated curtain was placed in the middle of the water tank. A pump was used to send the cooling water in the tank to the gearbox.

2.2 Test Gears

The tooth surfaces of the gear should show a good resistance to wear and should have good fatigue resistance because they are exposed to repeated loadings during the operation. Therefore in this study, after considering the working conditions of the gear, spheroidal graphite cast iron was used as the gear material. The chemical composition of the material used is shown in Table 1. Abrasion resistance of spheroidal graphite cast iron is good. The reason for this is due to the graphite content [25]. For this reason, spheroidal graphite cast iron was used as gear material in the experiments.

Table 1. The chemical composition of spheroidal graphite cast iron

%C	%Si	%Mn	%P	%S	%Mg	%Cr	%Ni	%Mo	%Cu	%Al	%Ti	%Sn
3.40	2.69	0.19	0.02	0.01	0.044	0.04	0.73	0.23	0.87	0.015	0.004	0.007

The features of the gear wheels used in the experiments and in the manufactured gear wear experimental device are given in Table 2 and the manufactured test gear is shown in Figure 3.

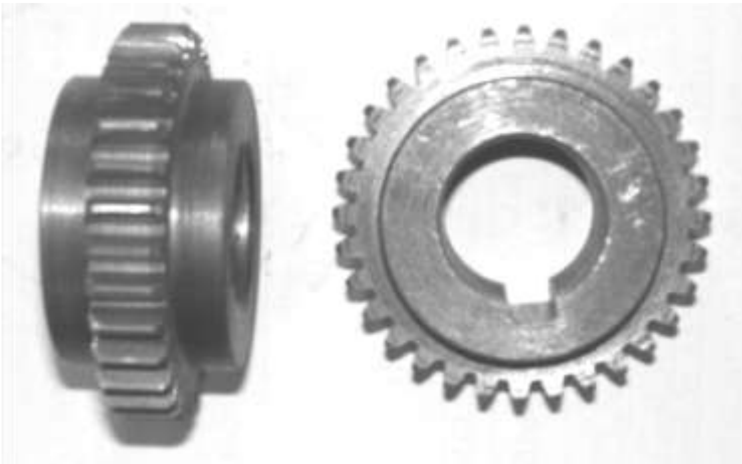

Figure 3. Test Gear

Table 2 The specifications of the test gears

Test gears	
Number of teeth	32
Module, (mm)	2
Pressure angle	20^{o}
Tooth width, (mm)	10
Pitch circle diameter, (mm)	64
Major diameter (mm)	68
Tooth height (mm)	4,332
Step tooth (mm)	6,28
Hardness (HRB)	83

2.3. Experimental Oil Properties

The SAE EP 80 gear oil was used. This is multi-purpose high-performance power transmission oil which was developed to be used in the oil-bath, hydraulic, and transmission brake systems of tractors and construction machines (Table 3). Due to its high-quality base oils and additive composition, it provides excellent sound control in oil bath brake systems and transmission units. It is used in transmission units, brakes, hydraulic systems, final drive units, differentials, and transmissions of tractors and construction machines [26].

Table 3. Experimental oil properties [26]

SAE viscosity grade	80
Density at 15 ° C, g / ml	0.88
Viscosity at 100 ° C, cSt	10.6
Viscosity index	102
Flash point, ° C	190
Pour point, ° C	-28

3. Results and Discussion

3.1. Material Loss Test Results

During the material loss experiments, the amount of loss was identified by weighing the gears before and after the experiment. In order to detect the amount of material loss, a scale with 0.01 g sensitivity was used in the experiments.

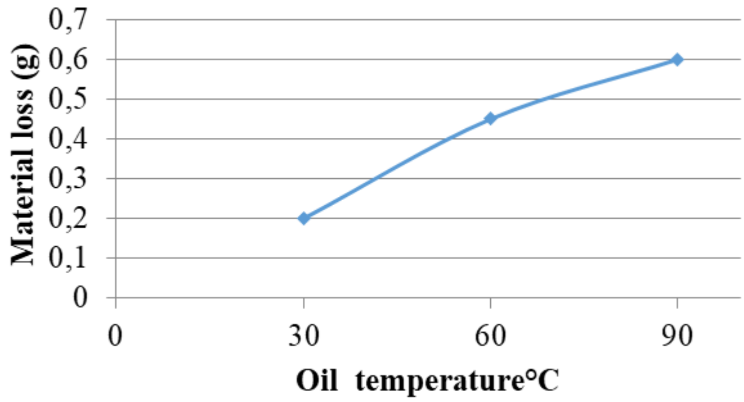

Figure 4. Results of experiments with different temperature

In Figure 4, the graph of oil viscosity and material loss is shown. Figure 4 reveals when examined that loss of material gradually increases depending on operating temperature. As a result of reduction in oil viscosity as temperature rises, load-bearing ability of oil under pressure decreases. This is why the oil film between the surfaces of gear teeth tears and the amount of material coming off from the gear wheel surface increases. Wear also increases depending on the reducing viscosity.

3.2. Surface Roughness Test

Surface roughness values were taken from three pieces of teeth for each sample with a Perthometer device. As a result of the experiments, the gear surfaces were evaluated based on the (Ra) average roughness values. Before starting the fatigue experiment, the initial roughness values of the gears were measured as 1,210 Ra on average.

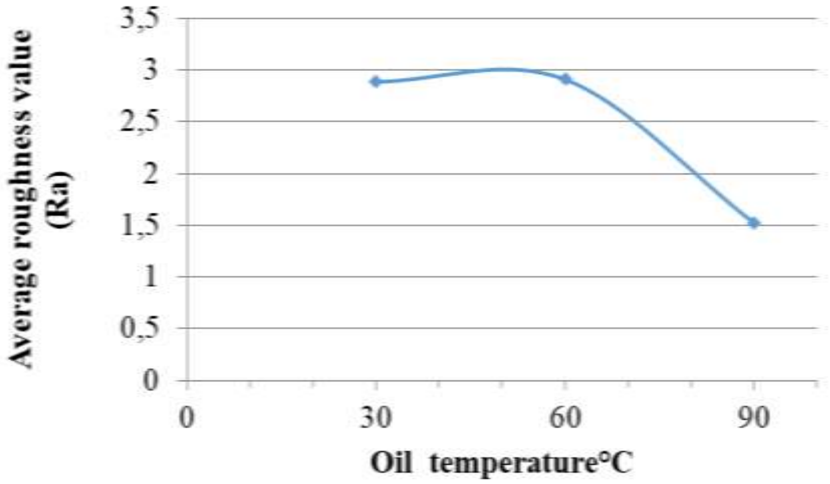

Figure 5. Roughness compared to with the value of the temperature

Figure 5 reveals when examined that roughness values at 30°C and 60°C are high and close to each other. Oil used at 30°C and 60°C preserves its lubrication capability. Film layer infused between the teeth surfaces tears when maximum force is reached between the two teeth, and since friction is at maximum, surface damages occur in these regions after a certain period of time. As the formed pitting damage occurs in a narrow region on the tips of gear wheels, mean roughness values turned out to be higher. Oil film between teeth surfaces disappear completely due to the fact that oil loses its lubrication ability at 90°C, and wear occurs on the entire surface of the teeth. Thus, mean surface roughness values tend to decrease.

3.3. SEM Analysis of Surface Defects

Each gear was tested under the same load for five million cycles. To analyses gear surfaces, two samples from each gear were cut and then examined under a microscope. For the analysis, 42× and 200× magnification was performed. For the surface analyses, a scanning electron microscope (SEM) was used.

When examined SEM images, it may be observed that pitting formation occurs on the tips of teeth. Pitting was found to occur in varying sizes. The reason for this was believed to be due to temperature. Oil viscosity reduced depending on temperature, and thanks to this, pitting size and amounts demonstrated an increase. Figure 6 shows SEM images from the samples at 30°C, 60°C, and 90°C temperatures, respectively.

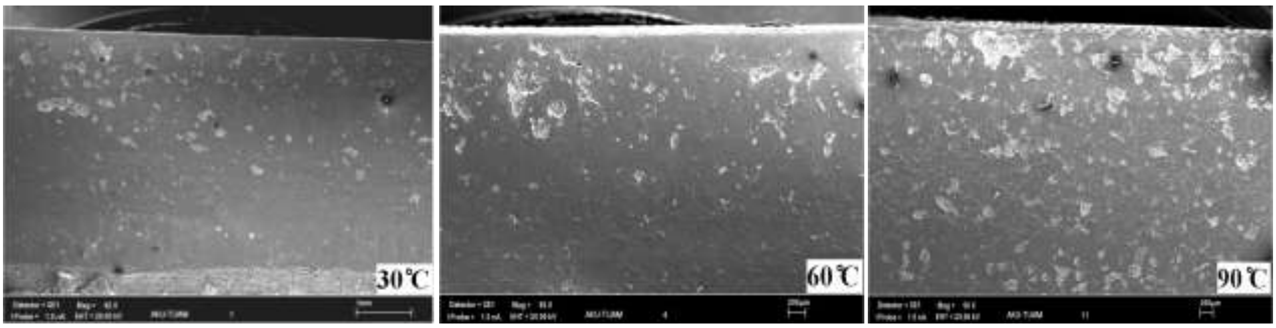

Figure 6. Different temperatures and surface images of worn gear

In experiments conducted at lower temperatures, pitting formation occurred at the tip of the teeth. Pitting formation spreads to the entire tooth surface due to increasing oil temperature. It may be noted that there was rather a rolling movement under lower temperatures at the spot where the tooth had first contact (tooth tip). Since contact area was less at the initial moment of coupling during the gear wheel operation under lower temperatures, film layer formed on tooth surfaces could not bear the force applied on gear wheels, and wear occurred first at the tips of teeth. At the moment when gear wheel coupled entirely, contact surface area widened and force applied on area per unit reduced. This is why the amount of wear became less in base sections of gear wheels. However, oil viscosity decreases as the temperature rises and load-bearing ability of film layer occurring on teeth surface is reduced. Since, for this reason, film layer could not bear the load applied on teeth along with the increasing temperature wear occurs on the entire surface of the gear wheel.

When overviewed the surface examinations, breaks and fractures were found to have an irregular structure. Pittings formed bigger pittings by growing around themselves thanks to surface cracks formed or by merging with smaller ones in close proximity in time (Fig 7.).

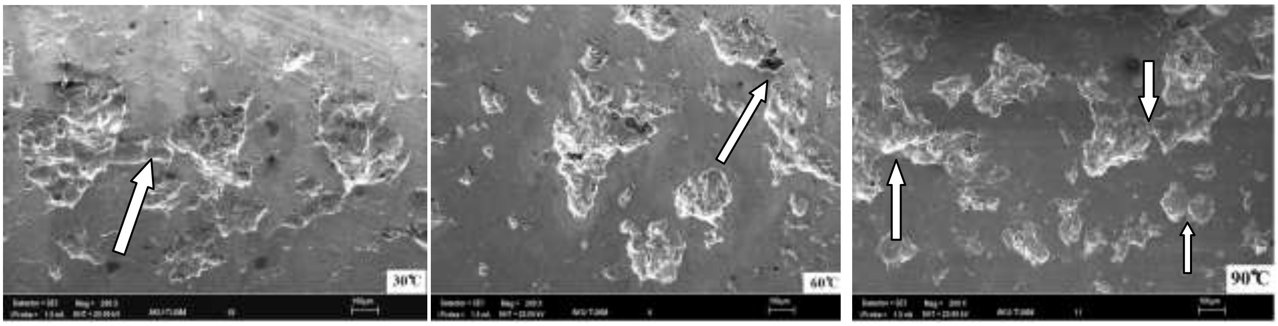

Figure 7. Surface Cracks (Zoom X 200)

As a result of surface fatigue tests, it was concluded that the extent of pitting damages occurring on teeth surfaces and gear wheel life were significantly affected by changes in oil temperature since amount and extent of pitting developed on gear wheels with high oil temperature were more compared to lower temperatures (Table 4).

Table 4 Experiments pitting size

Test Gear	Oil temp. (^oC)	Pitting size (µm)
1	30	450
2	60	800
3	90	870

4. Conclusions

When examined the gear wheel surfaces, it was established that pittings were occurred in irregular form. Pitting sizes were observed to increase parallel to rise in oil temperature. Initially, pittings are in small sizes, however, surface cracks are formed between pittings in time and such cracks merge them and cause the formation of a larger pitting. Maximum pitting size was measured at about 870 µm at 90 ºC oil temperature, and the lowest pitting size was measured as approximately 450 µm in tests performed at 30 ºC.

In tests conducted at lower temperatures, pitting formation developed at the tip of tooth. Pitting formation has spread to the entire tooth surface along with the increasing oil temperature. As a result of the conducted experiments, the amount of material coming off from the gear wheel surface increased gradually depending on the operating temperature of oil.

Although mean roughness values were high and in juxtaposition in experiments conducted at 30°C and 60°C, mean roughness value decreased in experiments carried out at 90°C.

Acknowledgments

The Authors are grateful to Afyon Kocatepe University Scientific Research Project Funding (051.TEF.07) for financial support to this study.

References

[1]. Başaran, B., “Helisel dişli çarklarda pitting oluşumunun deneysel incelenmesi”, Yüksek Lisans Tezi, Gazi Üniversitesi, Fen Bilimleri Enstitüsü, 2001, Ankara.
[2]. Güneş, İ.V., Feyzullahoğlu, E., “The Adhesive Wear Properties of Rubber Conveyor Belt Materials Exposed to Different Working Conditions”, El-Cezerî Journal of Science and Engineering, 2019, 6(1); 131-139.
[3]. Shen,Z., Qiao B., Yang L., Luo W., Yang Z, Chen X., “Fault mechanism and dynamic modeling of planetary gear with gear wear”, Mechanism and Machine Theory, 2021, 155,104098
[4]. Flodin, S. A. “Simulation of mild wear in helical gears” Wear, 2000, 241, 123-128
[5]. Bajpai P., Kahraman A., Anderson N.E., “A surface wear prediction methodology for parallel-axis gear pairs” J. Tribol.-Trans. ASME, 2004, 126, 597-605
[6]. Akbarzadeh S., Khonsari M. M., “Prediction of Steady State Adhesive Wear in Spur Gears Using the EHL Load Sharing Concept”, J. Tribol. -Trans. ASME, 2009, 131, 5
[7]. Osman T., Velex P., Static and dynamic simulations of mild abrasive wear in wide-faced solid spur and helical gears”, Mech. Mach. Theory, 2010, 45, 911-924
[8]. Masjedi M., Khonsari M. M., “On the prediction of steady-state wear rate in spur gears”, Wear, 2015, 342, 234-243
[9]. Brandao J. A., Cerqueira P., Seabra J. H. O., Castro M. J. D., “Measurement of mean wear coefficient during gear tests under various operating conditions”, Tribology Int., 2016, 102, 61-69
[10]. Wojnarowski J., Onishchenko V., “Tooth wear effects on spur gear”, Dynamics Mech. Mach. Theory”, 2003, 38,161-178
[11]. Chen Z., Zhou Z., Zhai W., Wang K., “Improved analytical calculation model of spur gear mesh excitations with tooth profile deviations” Mechanism and Machine Theory, 2020, 103838
[12]. Atanasiu V., Oprişan C., Leohchi D., “The effect of tooth wear on the dynamic transmission error of helical gears with smaller number of pinion teeth”, Trans Tech Publ, 2014, 649-653
[13]. Shareef I., Krantz T. L., Wasiq A. M. A., “Influence of Surface Pitting and Friction Coefficient on the Static Transmission Error in Spur Gears” International Journal of Mechanical Engineering and Robotics Research, 2020, 9, 3, 314-323
[14]. Liu X.Z., Yang Y.H., Zhang J., “Investigation on coupling effects between surface wear and dynamics in a spur gear system” Tribol. Int., 2016, 101, 383-394
[15]. Brethee K. F., Zhen D., Gu F., Ball A.D., “Helical gear wear monitoring: modelling and experimental validation”, Mech. Mach. Theory, 2017, 117, 210-229
[16]. Shen Z., Qiao B., Yang L., Luo W., Chen X., “Evaluating the influence of tooth surface wear on TVMS of planetary gear set”, Mech. Mach. Theory, 2019, 136, 206-223
[17]. Ding H., Kahraman A., “Interactions between nonlinear spur gear dynamics and surface wear”, J. Sound Vibr., 2007, 307, 662-679

[18]. Amarnath M., Chandramohan S., Seetharaman S., "Experimental investigations of surface wear assessment of spur gear teeth", Journal of Vibration and Control, 2012, 18, 1009-1024
[19]. Wu S., Zhang H., Wang X., Peng Z., Yang K., Zhu W., "Influence of the backlash generated by tooth accumulated wear on dynamic behavior of compound planetary gear set", Proceedings of the Institution of Mechanical Engineers Part C: Journal of Mechanical Engineering Science, 2016, 231, 2025-2041
[20]. Padgornik, B., Vizintin, J., "Wear resistance of plasma and pulse plasma nitrided gears", Gear Tecnology, 2003, 33–37
[21]. Yavuz, I., Kizilaslan, K., Mutlu, I., "Effect of oil viscosity on the gear surface fatigue damages", Journal of The Balkan Trıbologıcal Association, 2014, 20, 615-624
[22]. Dempsey, P.J., Gear Damage Detection Using Oil Debris Analysis, 2001, Nasa/TM- 210936
[23]. Meshari A.A., Zahrani E.A., Diab M., "Failure analysis of cooling fan gearbox", Engineering Failure Analysis, 2012, 20, 166–172
[24]. Fontanari V., Benedetti M., Straffelini G., Girardi C., Giordanino L., "Tribologıcal behaviour of the bronze-steel pair for worm gearing", Wear, 2013, 300, 1-2, 1520-1527
[25]. Yetgin, S. H., Çolak, M., "Investigation of Mechanical and Tribological Properties of Graphite Filled Polypropylene Composites" El-Cezerî Journal of Science and Engineering, 2020, 7 (2); 649-658.
[26]. Hani, İ., "Madeni yağlar ve petrol ofisi ürünleri", Petrol ofisi A.Ş. Madeni Yağ Direktörlüğü, 2002, İstanbul.