Effect of oil viscosity on the gear surface fatigue damages

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Boundary lubrication

EFFECT OF OIL VISCOSITY ON THE GEAR SURFACE FATIGUE DAMAGES

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ABSTRACT

In this study, the effects of different oil viscosities on gear wheels are investigated. In the experiments, the material of the test gear, number of cycles, temperature (30°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.

Keywords: gear damage, oil viscosity.

AIMS AND BACKGROUND

With developments in technology, the science of mechanics has enriched its content. In parallel with these developments, machine elements, the most important building blocks of mechanics, have contributed to innovations in design and manufacturing.

In recent years, the need for low-cost and high-quality new products in the field of production engineering has increased. Therefore, in order to provide time savings in the manufacturing sector, studies on the development of machine elements that can work at high speeds are carried out[1].

Gear wheels are machine elements that have been commonly used since ancient times. Although gear wheels can have different dimensions, materials, and applications, they are the elements that transmit motion and force through a shape bond between the input and output shafts in each machine[2].

Gear wheels, which offer engineering and cost advantages in the transmission of mechanical power, are used in many areas, such as automobile and airplane-

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space technology and sensitive devices like clock mechanisms. In recent years, in parallel with developments in engineering technology, the need for high-speed and heavy-load-carrying gear wheels has increased. The bending strain that occurs at the bottom of the load-carrying teeth is one of the barriers to meeting this need[3]. For decades, ongoing research has investigated the causes and types of deterioration incurred by gears in order to increase their resistance. Contact fatigue damage is a common mode of gear failure that generally manifests as the initiation and progression of micropitting on the flanks of the gear teeth[4–8]. Gears can fail in many different ways such as tooth breakage, scoring, pitting, and surface wear[9,10]. Gear surface wear is a phenomenon that takes place over a comparatively long period of time, affecting the functionality of a gear pair in two different ways. Both the vibration and the noise characteristics of the gear train are impacted[11–13]. Many studies on gear damage have been carried out. These studies can be divided into two groups.

The first are those studies focused on theory and analysis programs. Some of these studies are as follows: Wu et al.[14] carried out research on gear damages by developing a new model. In these studies, they examined the effects of functions on the gear such as the refraction angle and the rotation angle. Chaari et al.[15] developed an analytical sample in order to measure the gear contact area and the cracks in the gears. Additionally, Chen et al.[16] proposed a new gear network structure for the analytical calculation of the depth of the crack and the width of the teeth. Liu et al.[17] studied the effect of speed on lubrication performance comprehensively through its direct influence on lubrication and indirect influence by affecting dynamic loads of the gear pair. As a result, the dynamic load might be intermittent in high-speed cases that are close to the resonance frequency or superharmonic frequencies. At the transient intermittent phase of a dynamic load, a significant decrease in film thickness was observed.

The other group comprises the experimental studies, some of which are as follows. Moorthy and Shaw[18] investigated the effect of surface cladding of helical gears on fatigue damage. They concluded that the formation of damage in cladded gears was less than that in uncladded gears. In a study by Choy et al.[19], special features in the vibration signatures for each type of damage were identified and categorised. Using the categorised results, general conclusions were drawn concerning the identification of both individual and combined gear tooth and rolling element bearing damages.

Marjanovic et al.[20] carried out an experimental determination of the friction coefficient on a pin-on-disk tribometer. Dependencies of the friction coefficient on sliding speed and contact pressure were predicted based on the data obtained by measurement. Pasaribu and Lugt[21] proposed a semi-empirical equation to correlate the composition of the reaction layer (i.e. the oxygen, phosphorus, and sulfur concentration profile) with bearing performance. Plausible mechanisms of the

observed correlation are discussed. The results presented in this article reveal that bearing performance is reduced when the reaction layers formed by additives in lubricating oil are composed mainly of high concentrations of sulfur and phosphorus in combination with a low concentration of oxygen.

Gear wheels erode over time, resulting in negative consequences. As a result of investigations, studies have proposed that the corrosion in gear wheels is related to many factors. One of the most important of these factors is the viscosity of oils. Pitting damage, a type of wear, is derived from inadequate lubrication conditions.

EXPERIMENTAL

In the experiments, the material of the test gear, number of cycles, temperature (30°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.

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 Fig. 1.

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

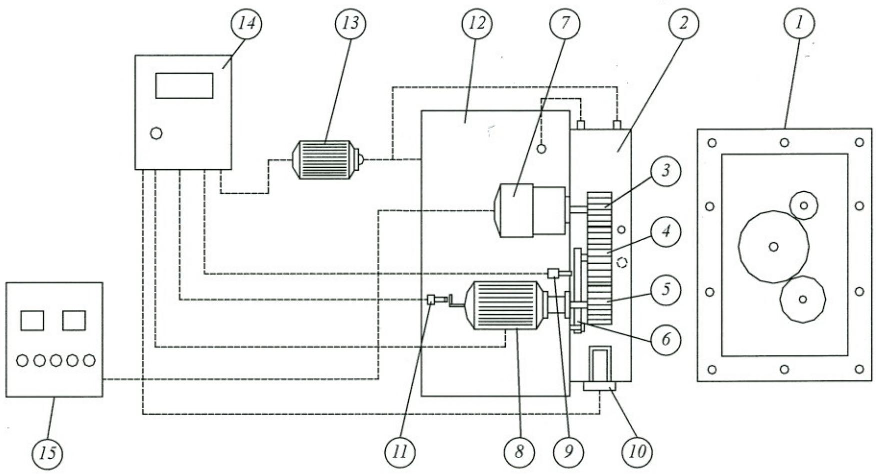


Fig. 1. Schematic view of the device

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 Fig. 2.

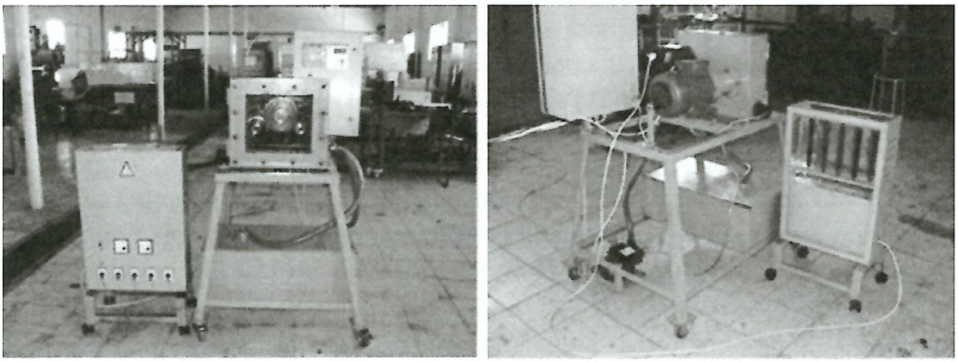


Fig. 2. Gear appearance of fatigue test device

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.

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.

Table 1. 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 Fig. 3.

Experimental oil properties. Oils of three different viscosities were used in the experiment (Table 3). The first of them, SAE 30, is usually used as motor oil. However, in some cases, this oil is also used in some gearboxes. It is especially used in the gearboxes of tractors and similar vehicles.

Secondly, 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. 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[22].

The third oil tested was SAE EP 140 gear oil. This extreme-pressure gear oil is developed by adding rust- and wear-preventive and an extreme-pressure-resistant special package additive to a paraffinic essential oil base. It is used in medium conditions in automotive differentials, manual gearboxes, and hypoid gears in high-speedlow-torque and low-speedhigh-torque conditions, and also in heavy duty trucks and construction machines[23].

Table 2. The specifications of the test gears

Parameter	Test gears
Number of teeth	32
Module (mm)	2
Pressure angle	20°
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

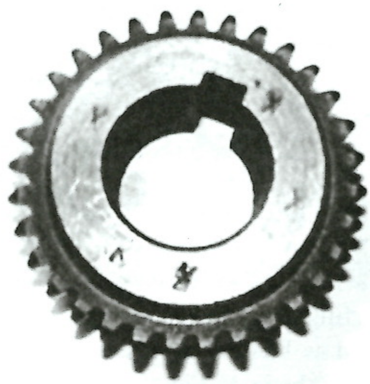


Fig. 3. Test gear

Table 3. Experimental oil properties[21]

Properties	SAE viscosity grade		
	30	80	140
Density at 15°C (g/ml)	0.88	0.88	0.906
Viscosity at 100°C (cSt)	10.8	10.6	31
Viscosity index	98	102	92
Flash point (°C)	238	190	250
Pour point (°C)	–21	–28	–10

TEST RESULTS

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. In Fig. 4, the graph of oil viscosity and material loss is shown.

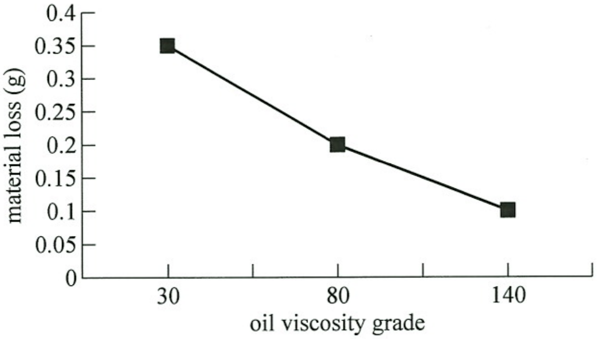


Fig. 4 Results of experiments with different viscosities

An analysis of Fig. 4 shows that the material loss value decreases when the viscosity increases. As the viscosity increases, the ability of the lubricant film strength is also increasing. As a result of this, the corrosion on the gear surfaces decreases. As the viscosity decreases, the oil film tears more quickly so the wear on the gear surfaces increases to maximum levels.

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 (R_a) average roughness values. Before starting the fatigue experiment, the initial roughness values of the gears were measured as 1.210 R_a on average.

An analysis of Fig. 5 shows that the roughness value decreases when the viscosity increases, just as in the material loss experiment. As the viscosity increases, the oil film is based on larger loads. As a result of this, the wear (pitting) on the gear surfaces decreases. As the viscosity decreases, the oil film tears very quickly and the roughness values of the gear surfaces increase.

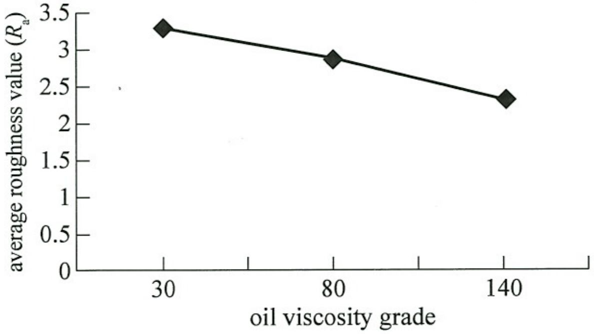
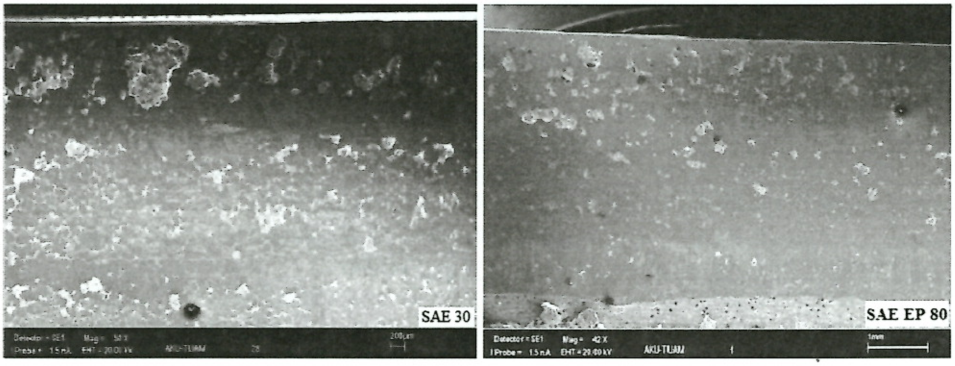


Fig. 5 Roughness compared to with the value of the viscosity

SEM analysis of surface defects. Each gear was tested under the same load for five million cycles. To analyse the gear surfaces, two samples from each gear were cut and then examined under a microscope. For the analysis, 50× and 200× magnifi-

cation was performed. For the surface analyses, a scanning electron microscope (SEM) at Afyon Kocatepe University Technology Application and Research Centre was used.

As viscosity increases, the roughness value decreases. Because the tearing the film layer under the load occurs more easily between thin oils and teeth surfaces. As a result of the change in the oil viscosity, the pitting damage occurring on the gear surfaces indicates variety. In Fig. 6, the 30, 80, 140 viscosity oils and the SEM photographs taken from the samples used are displayed.



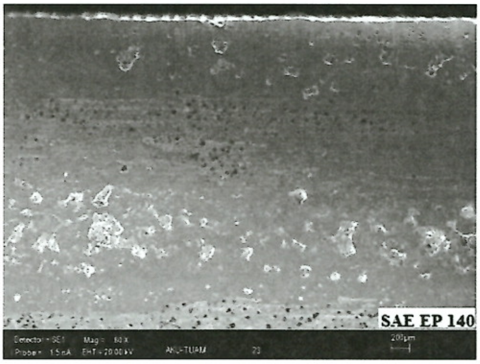


Fig. 6. Different viscosities and surface images of worn gear

Considering the general views of the surface examinations in the experiments, pitting formation occurred at the edge of the teeth. When the gear surface was analysed in the experiment where only the 140 gear oil was used, it was observed that the pitting increased towards the bottom of the teeth. The sizes of the pits are different, and they increase in size with a decrease in viscosity.

A 200× magnified SEM picture of the gear in which the SAE 30 gear oil was used and which shows maximum surface fatigue damage is given in Fig. 7. When the surface investigations were considered in general, it was observed that the fractures had an irregular structure. As the surface cracks proceeded, they caused material loss in layers from the surface.

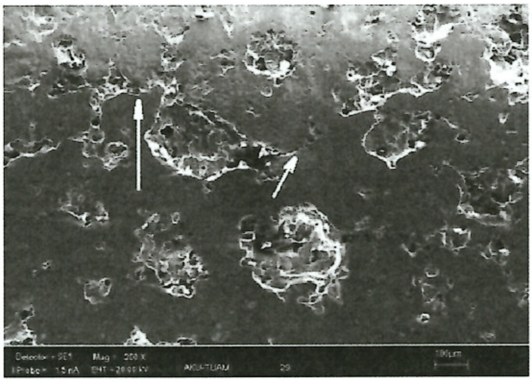


Fig. 7. Surface cracks

Table 4. Experiments pitting size

Test gear	Oil viscosity grade	Pitting size (μm)
1	30	900
2	80	450
3	140	335

At the end of the fatigue experiments it was observed that the change of viscosity significantly affected the size and lifetime of the pitting damage that occurred on the teeth surfaces because the amount and size of pits occurring on the teeth with low oil viscosity increased compared to the others (Table 4).

CONCLUSIONS

- According to the results of the surface roughness tests, as the oil viscosity decreases, the surface roughness and material loss increase.
- The SEM photographs show that the pits were concentrated at the edge and had an irregular structure. As the oil viscosity used in the experiments decreases, the pitting dimensions increase.
- As the viscosity increases, pitting formation decreases and less surface damage occurs.
- At the end of the fatigue experiments it was observed that the change of the viscosity significantly affected the size and lifetime of the pitting damages that occur on the teeth surfaces.
- It was observed that the fractures occurred on the surface in an irregular structure. As the surface cracks proceed, they cause material loss in layers from the surface.

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