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Effect of tooth profile modification on wear in internal gears

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Abstract. Internal gears are often used in the automotive industry when two gears are required to rotate in the same direction. Tooth shapes, slippage speeds at the beginning and end of meshing are different according to the external gears. Manufacturing of internal gears is more difficult than external gears. Thus, it is necessary to determine the working conditions and wear behavior of internal gears carefully. The profile modification method in terms of strength and surface tension of the gear mechanism are performed in order to increase the load-carrying capability. In this study, profile modification method was performed in the internal gears to reduce the wear on the teeth. For this purpose, the wear of the internal gears was theoretically investigated by adapting the Archard wear equation to the internal gears. Closed circuit power circulation system was designed and manufactured to experimentally investigate the wear in internal gears. With this system, wear tests of gears made of St 50 material without profile modification and different profile modifications were made and the results were compared. Experimental study was performed in the same loading and cycle time conditions to validate the theoretical results and it was seen that the results are compatible. According to the experimental results, it is seen that in the internal gears, when profile modification done the wear is decreased in the teeth tip region.

1. Introduction

Internal gears are different from the external gears in that their teeth are turned inward rather than outside the gear center. Internal gears having concave tooth profile mate with external gears having convex tooth profile which provides some advantages; low contact stress, low sliding velocity and high gear ratio [1]. Internal gears are widely used in automotive and aerospace industries, differential boxes and cranes as external sun gears of planetary mechanisms due to their compact structure, large torque-to-weight ratio, high gear ratio, reduced noise and vibration, etc [2].

Tooth profile modification; to increase the load carrying capacity of the gear mechanisms in terms of strength and surface pressure, to prevent the undercutting, to set the gear mechanisms between the gear axle offset, to reduce the slippage between the gears and accordingly to reduce the wear [3]. Several theoretical and experimental studies have been carried out on internal gears. In studies carried out to the geometry of internal gears; the effect of the rim thickness on the root stresses was investigated experimentally and theoretically [4-6]. These studies provide the manufacturing of internal gears with optimum rim thicknesses. In studies to examine the stresses in the tooth root of internal gears; effect of tensile and compression stresses in gear root examined [7-9]. Analytical formulations, finite element simulations, strain-gauge and photoelasticity based experimental procedures were used in stress measurements in these studies. Several studies have been carried out in order to prevent wear in internal gears [10-11]. In these studies, internal gears were covered with coating material to prevent wear. In this study, tooth profile modification method was used in the gears to reduce wear on the internal gears. The wear occurred in the gears without profile modification and a different profile modification under the same conditions was compared in theoretically and experimentally.

2. Wear model in internal gears

The teeth of the gears, which are in contact with each other, make sliding and rolling. As a consequence of these movements, wear occurs on the surfaces of gears. In the Archard wear equation[12];

$$\frac{V}{s} = K\frac{W}{H} \tag{1}$$

(V) is volume of the abraded material, (s) is slippage distance between two surfaces, (K) is the friction coefficient, (W) is applied load and (H) is surface hardness of the material. In order to use this equation in gears, it is necessary to take into consideration the sliding and rolling which show differences from the beginning to the end of the contact of the teeth. Flodin [13] adapted this equation to external gears.

$$h_p = \int_0^s kPds \tag{2}$$

Here; (h_p) is the wear depth in point (p), (s) is the sliding distance between two contacting surfaces, (k) is the wear coefficient and (P) is the regional contact pressure. To contacting gear pairs, namely expressing wear of any contacting point of tooth profiles of pinion-internal gear during coupling depending on rotation cycle count, wear depth at a point (p) after (n) cycle count can be expressed;

$$h_{p,n} = h_{p,(n-1)} + kP_{p,(n-1)}s_p \tag{3}$$

where ($h_{p,n-1}$) is the wear depth of same point in the previous cycle, ($P_{p,n-1}$) is the pressure at point (p) in the previous cycle and (s_p) is the sliding distance of point (p). In order to determine the slip distance at the contact points, examine the two points, p_1 and p_2, which are opposite to each other, from the teeth of the pinion and the internal gear through the coupling. These points were investigated in three different positions during the coupling. In the first position, p_1 and p_2 coincide in the beginning of contact and there is no difference in distance between them. In the second position; when p_1 is exiting coupling, p_2 is still in contact region. Thus, there is a distance of s_{p1} between p_1 and p_2. In the third position; when p_2 is exiting coupling, there is a distance of s_{p2} between p_1 and p_2. Point p_2 moves a distance of $2a_H.(U_2/U_1)$ when p_1 moves a distance of $2a_H$ (Hertz contact length) along the contact length in the contacting teeth pair where U_1 and U_2 are peripheral speeds of pinion and internal gear along the contact line, respectively. Similarly, p_1 moves a distance of $2a_H.(U_1/U_2)$ when p_2 moves a distance of 2a along the contact length in the contacting teeth pair.

$$s_{p1} = 2a_H\left(\frac{U_1 - U_2}{U_1}\right) \quad ; \quad s_{p2} = 2a_H\left(\frac{U_2 - U_1}{U_2}\right) \tag{4,5}$$

If equations 4 and 5 are written in Equation 3, wear depth equations for pinion and internal gear are respectively;

$$h_{p,n} = h_{p,(n-1)} + kP_{p,(n-1)}^{2} a_{H} \left(1 - \frac{U_2}{U_1}\right) \;;\; h_{p,n} = h_{p,(n-1)} + kP_{p,(n-1)}^{2} a_{H} \left(1 - \frac{U_1}{U_2}\right) \quad (6,7)$$

Pinion and internal gears peripheral speeds (U_1,U_2), Hertz pressure on the contact points of the teeth profiles (P) and Hertz contact area of tooth profiles (a_H) described in the previous work [10].

3. Experimental study

3.1. Test gears

The teeth numbers of pinion and internal gears used in the tests were 17 and 75 respectively and they were manufactured from St50 steel. The surface hardnesses of the gears were 160-170 HB. In the experiments, gears without profile modification, 0.095, 0.195 and 0.410 profile modification gears were used.

3.2. Test equipment

A pinion-internal gear fatigue and wear testing apparatus having the same working principle with the FZG [13-16] closed circuit power system was manufactured to perform wear tests (Figure 1). The apparatus which allows investigation of wear in various load and speed conditions seen in Figure 1 consists of two gear boxes having same gear ratio. There are control panels in the test setup where the temperature control and the number of revolutions of the driven motor can be adjusted. The system is loaded with 100 Nm and the motor speed is constant at 1500 rpm.

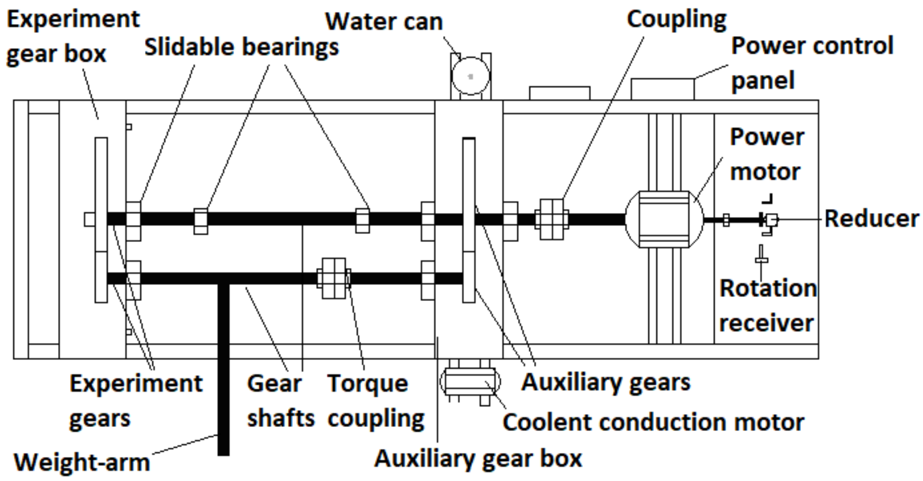
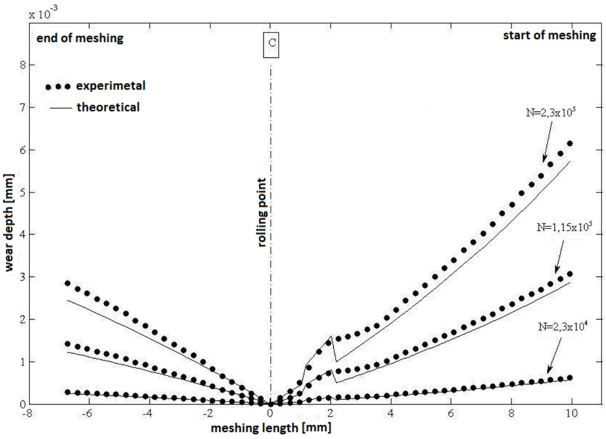


Figure1. Schematic drawing of testing apparatus

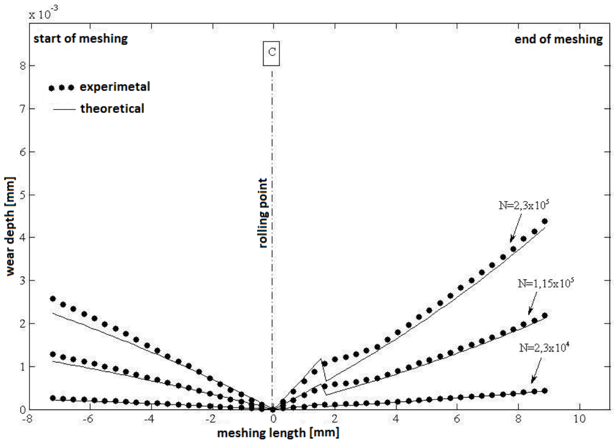
In the experiments, immersion type lubrication system was used. The oil temperature is kept constant at 23 ± 2 ° C due to the heater-cooler system.

4. Theoretical and experimental results

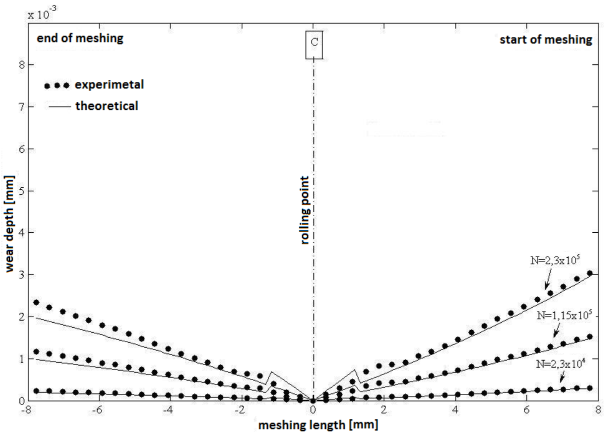
In order to investigate wear in internal gears, Archards' wear formulation was adapted to internal gears and wear behaviour in different tooth profile modification was determined in the theoretical part of the study with a MATLAB® code written for the obtained formulation. A fatigue and wear testing apparatus having similar working principle with FZG closed circuit power circulation system was designed and manufactured to experimentally investigate the wear in internal gears. the experimental wear depth values were measured with the help of CMM (Coordinate Measuring Machines) [10].



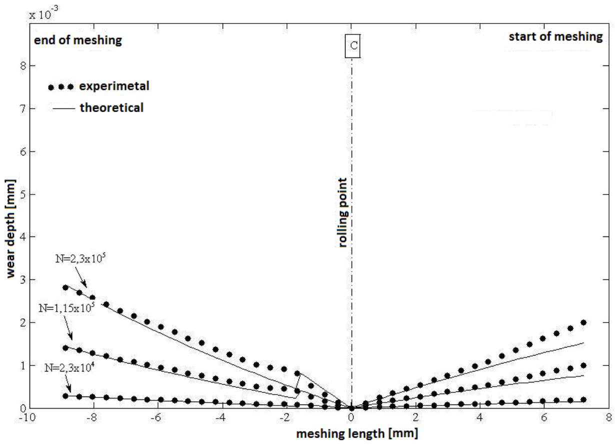
(a) Without profile modification



(b) x_1=x_2=0.095 tooth profile modification



(c) x_1=x_2=0.195 tooth profile modification



(d) x_1=x_2=0.410 tooth profile modification

Figure 2. Variation of wear depth of without profile modification and various profile modification internal gears with 1500 rpm motor speed and 100 Nm torque

According to both the theoretical and the experimental results (Fig.2), the maximum wear is seen in tooth tip region where the internal gear begins to coupling. When Figure 2 is examined, it is seen that experimental and theoretical results are compatible. The equation, which is theoretically used to determine the depth of wear occurring in the teeth, can be used with 2-3 % error when the difficulties of the manufacturing of internal gears, the duration of wear tests and working conditions are considered. When the wear depths of the internal gears without profile modification and different profile modification are theoretically and experimentally compared (Fig. 2 a-d); the wear depth values decrease by 18.4 %, 27.5 % and 39.2 % respectively, when the profile modification amount increases. When the amount of profile modification is increased in the internal gear, wear is reduced in the tooth tip region of the internal gears. However, when the amount of profile modification exceeds a certain amount, the length of entry of meshing reduced, thus the load will more effect the tooth root region and increase the wear depth (Fig. 2 a & d).

5. Conclusion

In this study, the tooth profile modification method was used to reduce the wear on the internal gears. Theoretical and experimental studies have been carried out to investigate the effect of the amount of profile modification on wear. Theoretical results are solved by using Matlab program and applied to internal gears under different profile modification conditions. Experimental studies have been carried out on the same conditions to confirm theoretical studies. As a result of this study, the following conclusions were reached.

1. The theoretical equation, which is adapted to internal gears and used with 2-3 % error in different speed and torque conditions, can be used for different profile modification amounts to measure the depth of wear of the internal gears.
2. The profile modification method in the internal gears is a method of increasing the strength of the teeth. Wear can be reduced by using the profile modification method in the internal gears. In internal gears when the amount of profile modification increases, the length of entry of meshing increases and the length of the exit of meshing decreases. In other words, the strength of the tooth tip region of the internal gear increases while the strength of the tooth root region decreases. For this reason, when profile modification is performed in the internal gears undercut of the teeth is take into consideration.

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