

# The Investigation of the Working Conditions on 3D Printed Helical Gears

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**Abstract:** Helical gears have a greater coupling advantage than spur gears; and transmit higher power and speed. In this study, the working conditions (surface roughness, noise emission and wear changes) of plastic helical gears produced using polylactic acid (PLA) in 3D printers were experimentally investigated at different loads and speeds. At the end of the study, it was observed that, as the amount of torque acting on the system increased, the wear of the plastic gear increased, whereas the wear decreased as the rotation speed increased. The surface roughness of plastic gears is high depending on the layer thickness during production. The roughness values decreased with acclimatization wear and then increased according to the operating conditions and surface deterioration began. The operating noise emission measurements of the system increased at high loads and speeds. Helical gears produced under the same conditions have 5-8% lower noise-emission values than spur gears and can be used more widely, especially in electric motors. Based on this study, it can be said that gears produced using the AM method can be an alternative to the plastic injection molding method, especially when a small number of parts is important.

**Keywords:** additive manufacturing; helical gear; noise-emission; surface roughness; wear

## 1 INTRODUCTION

3D printers produce modeled objects in layers without requiring additional equipment and extra mold. They have advantages such as being easy to use, not needing an additional molding system, and low investment and raw material costs. By giving infill density to the parts produced with 3D printers and obtaining lighter materials, both costs and production times can be reduced. Among the disadvantages of the system are that it is not suitable for mass production and although it is assumed that the production is done automatically by the printer, users must be experts to avoid errors that occur during the production stages.

Plastic helical gears are used to transfer power and motion, especially in electric motors, robots and drones. The choice of helical plastic gears is due to their quieter workings and resistance to loads. Plastic helical gears are generally produced by plastic injection molding and sintering methods.

Studies on plastic gears in the literature generally include examining the stresses occurring in the areas where the gears are on coupling, the effects of sound and vibrations on the gears, and the observed wear of the gears.

In plastic gears, Rigaud and Liaudet [1] describe impact sounds occurring between teeth; Lee and Yun [2] and Liu et al. [3] do vibration and sound tests and some researchers [4] investigated the effects of noise-emission. Pan and Yang [5] used the Barkhausen sound analysis method to examine gear damages in high-speed trains. They stated that incorrect grinding process caused loss of hardness and strength. Feng et al [6] examined the effect of coating materials on noise in gears with experiments at different rotation speeds. They determined that the GLC (graphite-like carbon) coating was significantly effective in reducing axial vibration and produced 10dB less noise at a rotation speed of 2000 rpm. Ramanjaneyulu et al. [7] improved the mechanical and tribological properties of the gears by adding graphene filling material to the gears produced by plastic injection molding. Kulkarni et al. [8] solved the noise problem in the gearbox in the ANSYS program using the Comsol Acoustic model. They stated that it is advantageous to use plastic gear instead of metallic

gears at 0,75 kW powers. Chopane et al. [9] stated that if the rack and pinion pair used in vehicles are produced with Nylon 66 material, the corrosion resistance will be better and it is more attractive due to its oil-free and quiet operation.

Some researchers have examined the stresses occurring in the areas where plastic gears are in coupling [10, 11]. Malakova et al. [12] stated that changes in the bevel gear engagement ratio cause additional stress and vibration on the tooth, and that more frequent and better lubrication will be effective in reducing the problem. Mughal et al. [13] stated that more than 80% of the deformation on the surface of gear pairs is elastoplastic deformation and that this deformation causes wear. Zorko et al. [14] investigated the relationship between center distance in gearboxes and assembly errors. In their studies, they stated that as the center distance increases, the service life increases by up to 30%. Vignesh and Mertens [15] stated that wear is caused by contact stresses occurring in the clutch. Bravo et al. [16] tried to reduce the friction force and the nominal load transmitted with the finite element analysis program they developed in plastic gears. In Mohsenzadeh et al. [17] damage mechanisms and service lives were examined by applying different torques to plastic spur gear pairs.

Researchers have carried out wear tests with gears made of PEEK (Polyetheretherketone) [18], POM (polyoxymethylene) [19] and Nylon 618 [20] materials. The wear behaviors of POM, HDPE, ABS, POM-h and PA 12 plastic gears produced by plastic injection molding method were examined at various rotation speeds [21, 22]. Zhe et al. [23] derived the wear resistance model of plastic gears. Some researchers [24, 25] conducted wear tests with plastic gears produced with a 3D printer. Mao et al. [26, 27] and Li et al. [28] carried out wear tests with acetal and nylon, and Dighe et al. [29] with composite gears at different loads and rotations.

In this study, the wear of plastic helical gears produced by 3D printers under different loads and rotations was experimentally examined. In addition, the surface roughness and operating noise-emission of the gears were observed.

## 2 MATERIALS AND METHOD

In this study, PLA (Polylactic acid) material was chosen because it is easy to find, there is no need for bed heating during production, and the parts stick easily to the bed and have no warping effect. PLA material is also easily recycled. It is used in most additive manufacturing processes that design 3D models and prototypes through plastic-based materials. St 37-2 gear was used as an attritive gear (Fig. 1). The specifications of the gears used in the tests are shown in Tab. 1. The PLA material used in the tests shows very good elongation behavior, although it is approximately equivalent to other polymeric materials in terms of tensile stress and shear modulus. It is not affected too much by the external environment during production. The properties of the material used in the tests are shown in Tab. 2.



Figure 1 Test gears

Table 1 Specifications of test gears

	Pinion	Gear
Materials	PLA	St37-2
Modulus of elasticity / MPa	3500	210000
Module	6	
Number of teeth	17	22
Pressure angle / °	20	
Helix angle / °	15	
Profile shift correction	0	
Dia. of pitch circle / mm	102	132
Dia. of tip circle / mm	113,6	143,6
Tooth width / mm	10	

Table 2 Properties of PLA material [25]

Density / g/cm <sup>3</sup>	1,3
Tensile Strength / MPa	50
Hardness (Shore D)	83
Poisson's ratio	0,36
Elongation at Break / %	6,0
Shear Modulus / GPa	2,4
Heat Deflection Temperature / °C	65
Specific Heat Capacity / J/kg-K	1800
Thermal Conductivity / W/m-K	0,13
Glass Transition Temperature / °C	60

Plastic gears are produced with 0,2 mm layer thickness. The first layer was chosen as 0,4 mm to ensure that the part adheres better to the manufacturing bed during the production phase and to prevent it from lifting off the bed and deteriorating the tooth profiles. Gears were produced at 100% infill density, 210°C extruder temperature and 60 mm/s speed (Tab. 3). Although there is no need to heat the table during production with PLA material in 3D printers, the table was heated at 60 °C. The reason for this is that in gear production, the production is

disrupted with the smallest tensile stresses, the gears cannot engage at the same rate and show unexpected wear behavior.

Table 3 Manufacturing stages of plastic gears

Material	PLA
Nozzle diameter / mm	0,4
Filament diameter / mm	1,75
Layer height / mm	0,2
First layer height / mm	0,4
Shells / mm	1,2
Infill density / %	100
Fill pattern	Concentric
Extruder temperature / °C	210
Bed heating temperature / °C	70
Printing speed / mm/s	60

The gears were rotated to a total number of  $10 \times 10^4$  revolutions at different loads (0,5, 1, 1,5 Nm) and speeds (300, 600, 900 rpm). The working conditions, such as surface roughness, noise emission and wear changes, were determined experimentally by operating the gears at different speeds and loads.

The FZG test device, which is used in wear and fatigue tests, was preferred in the tests (Fig. 2). FZG is a closed-circuit power circulation system widely used in wear and fatigue tests on gears. With this test rig, the wear of the gears at various loads and speeds is observed. The purpose of the test rig is to apply a torsional moment to the shaft connected to the gears and distribute this moment to the gears and thus perform wear test simulations under different conditions.

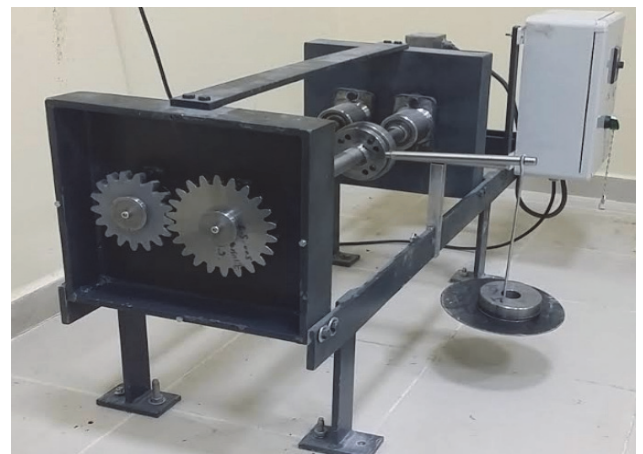


Figure 2 FZG test rig [25]

To determine the noise-emission measurement during working in gears, a microphone was placed in areas close to the gearbox connected to the FZG test device and measurements were taken from different points with the help of the Sirius ® program.

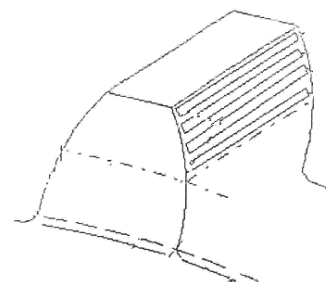


Figure 3 Surface roughness measurement regions

To observe the change in surface roughness of plastic helical gears, measurements were made from the areas where the gears are in coupling with the MahrSurf PS1 roughness device (Fig. 3). Measurements were taken before the test, after  $5$  and  $10 \times 10^4$  revolutions.

To examine the wear performance of plastic helical gears under different conditions, specific wear rates in total rotation revolutions were calculated and compared. The specific wear rates of mating gears are calculated as follows:

$$W_s = \frac{W_v}{2zxmxbxN_T} \quad (1)$$

where  $W_v$  is the wear volume ( $\text{mm}^3$ ),  $z$  is the number of plastic gear teeth,  $m$  is the module (mm),  $b$  is the tooth face width (mm),  $N_T$  is the total number of revolutions (rev). Wear volume ( $W_v$ ) is obtained by dividing the wear loss (or weight loss) over the density of the material of the gear.

### 3 RESULT and DISCUSSION

#### 3.1 Noise Emission Measurements of Helical Gears

Plastic helical gears are preferred over spur gears to reduce noise in the gearboxes of electric motors, drones and robots. The noise-emission levels of gears operating at different loads and speeds were measured and compared in Figs. 4 and 5.

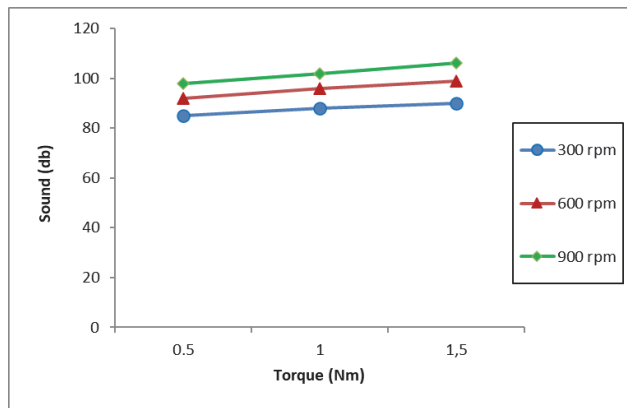


Figure 4 Noise-emission levels of helical gears at different loads and speeds

According to Fig. 4, it is observed that when the load and speed value of the system increases, the noise-emission values also increase. The increase in values was measured at 4-5% in torque and 10-12% in speed. Since the attritive gear on the plastic gear is steel, low torque values were used in the study and the noise-emission values seem to be low at these values. It is expected that the values will increase even more at higher torques.

The sound level of the test environment is 27 dB. When the test rig was running without a torque, sound levels were measured as  $70 \pm 2$  dB at 300 rpm,  $74 \pm 2$  dB at 600 rpm and  $78 \pm 2$  dB at 900 rpm rotation speed. When the system is loaded with 1,5 Nm torque, the sound level increases by 35% at 900 rpm, 106 dB. According to this result, after the torque, an understandable noise-emission difference is observed in the system. This difference will be increased as the wear rate increases. In future studies, increases in sound levels can be recorded at short intervals

and the development of wear on the gears can be examined without stopping the system.

It is generally known that helical gears are more quiet than spur gears due to the meshing length. To observe this, Fig. 5 was obtained by operating spur and helical gears produced under the same conditions where the noise-emission level was the highest (1,5 Nm and 900 rpm).

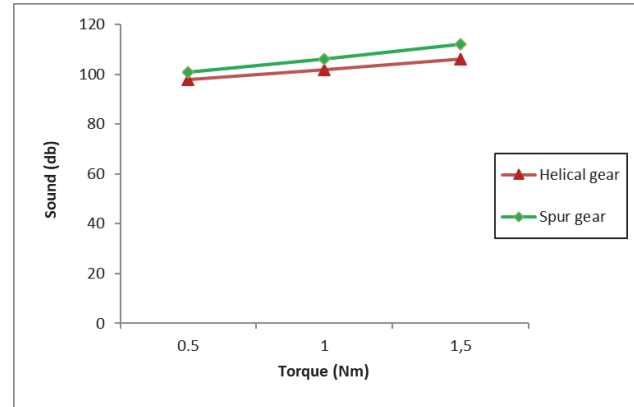


Figure 5 Sound-emission comparison of helical and spur gears

The helical gears used in the study are meshing 5% more than spur gears with the same manufacturing conditions. With a higher contact ratio, the teeth in the helical gear share the load reducing the level of noise. According to Fig. 5 the difference between the sound levels of helical and spur gears is 4% at low torques and 6% at high torques. As a result, the difference in sound level will gradually increase in systems operating at higher torques and the advantage of using helical gears will increase significantly.

#### 3.2 Surface Roughness of Plastic Helical Gears

Plastic helical gears are produced in layers using the additive manufacturing method (Fig. 6). Surface roughness measurements of gears are made perpendicular to the layers in the y-axis, which is the direction of production.

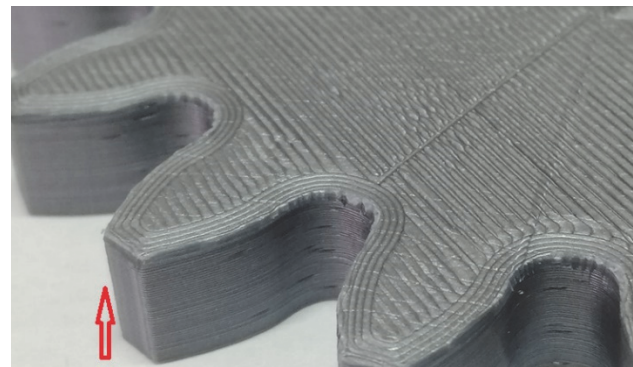


Figure 6 Manufacturing direction of test gears

Fig. 7 shows the surface roughness values of plastic gears under the conditions where wear is most seen (1,5 Nm and 300 rpm). According to Fig. 7a, the average Ra value along the measurement length of the gear before the test is around  $16,86 \mu\text{m}$  and is quite high in terms of roughness. It can be seen from Fig. 6 that since the layer thickness of the gears in production is 0,2 mm it is not sensitive in terms of roughness.

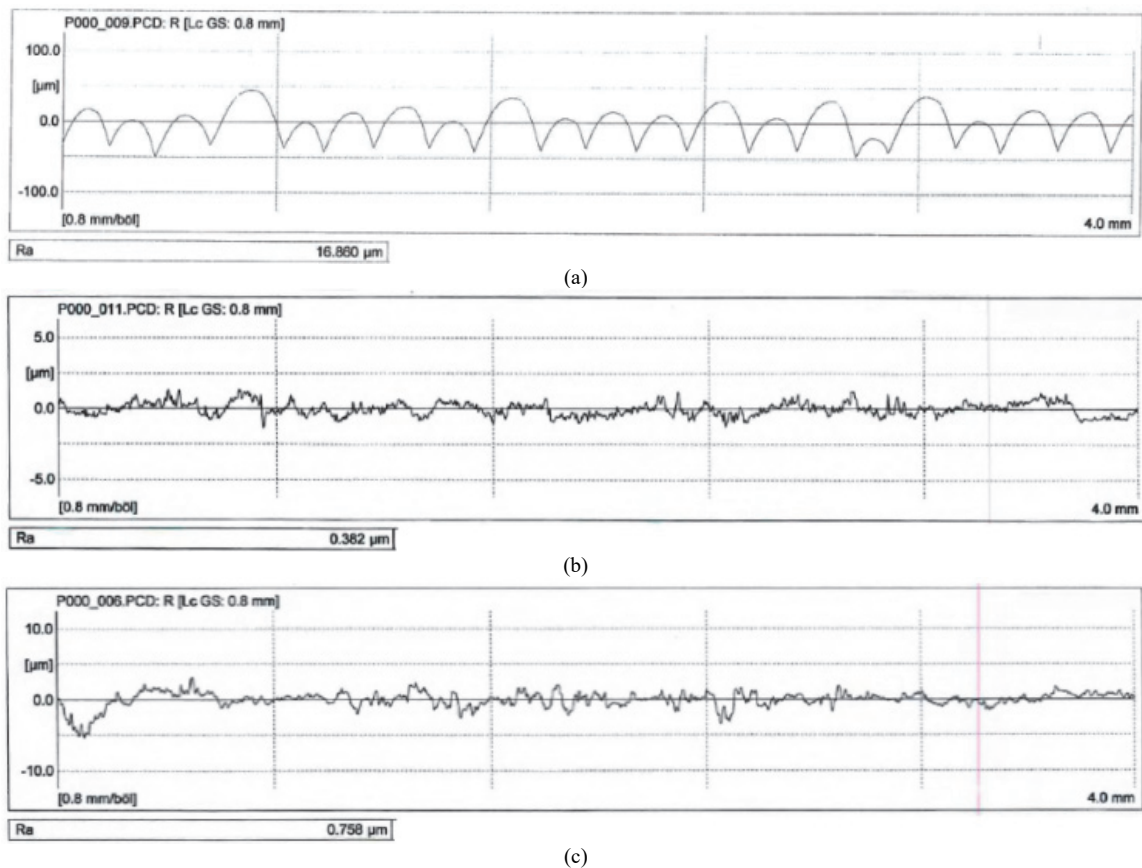


Figure 7 Surface roughness of plastic helical gears under 1,5 Nm and 300 rpm conditions  
(a) Before tests, (b)  $5 \times 10^4$  revolution, (c)  $10 \times 10^4$  revolution

In production the layer thickness of the gears can be selected depending on the nozzle diameter. More sensitive surfaces can be obtained by reducing the layer thickness and roughness values in production of the parts but when the layer thickness decreases, the manufacturing time of the gears increases at the same rate. In this study, the tooth width was taken as 10 mm for strength of the gears. Helical gears were manufactured in 50 layers with a layer thickness of 0,2 mm in 3 hours. Gears of the same size can be produced in 6 hours with a layer thickness of 0.1 mm. In addition, as the layer thickness decreases, the hot nozzle tip of the 3D printer gets closer to the produced part, causing the layers to have adhesion problems between each other. For these reasons, gears are produced with layer thicknesses of 0,1-0,2 mm [28]. According to Fig. 7 (b), when the gears rotate  $5 \times 10^4$  at 1.5 Nm load and 300 rpm speed, the layers wear out and the Ra value decreases to 0,362  $\mu\text{m}$ . When gears are coupling under load, their contact points wear out due to friction and the surface roughness decreases rapidly. In this study the plastic gears were worn out by the steel gears and the tooth surfaces became smooth as if they had been sanded. When mated gears are plastic, the worn particles will stick to the other and the wear of gears may show different behaviors. When the gears rotate at  $10 \times 10^4$  revolutions, the plastic gear begins to wear over time due to operation and the wear value increases to 0,758  $\mu\text{m}$ . Surface roughness values are measured at 1,5 Nm and 300 rpm conditions where wear is seen highest. The values are shown with similar characteristics under different loading and rotation conditions. Surface roughness values are high at first measurement due to manufacturing, the values decrease

because of the surfaces contact with each other in meshing. The surface begins to deteriorate due to the abrasive effect of the load and the roughness values increase.

### 3.3 Wear on Plastic Helical Gears

Wear is very important for the service life of the gears. Worn teeth quickly cause the gear to fail. Since the usage areas of plastic gears are generally located in the gearboxes of the motors, removing the damaged gear and renewal is a very costly and time-consuming process. Generally, these operations are performed by experts and incur additional costs. Compared to steel gears, plastic gears can be damaged quickly due to sudden heating where mating gears are meshing at high loads and speeds. For this purpose, the operating conditions of plastic gears at different loads and speeds should be carefully examined.

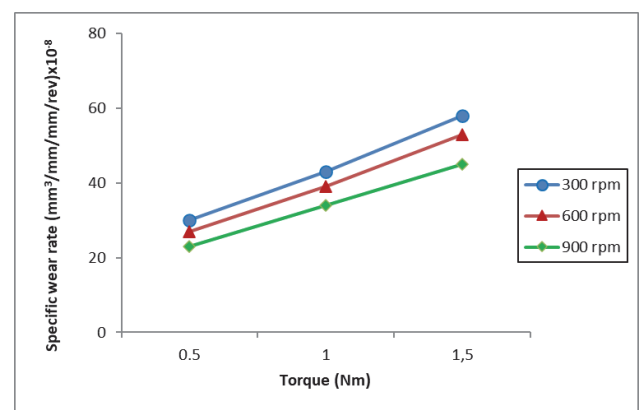


Figure 8 Wear behavior of plastic helical gears for different loads and speeds

Fig. 8 shows the specific wear rate change of plastic gears rotated for a total of  $10 \times 10^4$  revolutions at different speeds and loadings. This ratio is given in Eq. (1) and is used to calculate the wear on the gears. According to Fig. 8 when the speed increases, wear on plastic gears decreases by 15-20%. Gears work much at low speeds to complete the same number of revolutions. For example, in order to make the same revolution as a gear running at 900 rpm for 10 minutes, the gears have to work at 300 rpm for 30 minutes. More wear has been observed on plastic gears with long periods of working [25].

The load increase is very important in mating gears. Increasing the effect of load in the system causes sudden heating of the teeth in the meshing and quickly renders the gears unusable. According to Fig. 8 when the load effect increases by 50%, wear increases by 30-40%. The reason why the amount of wear is so high is that the attritive gear is steel. There is no such increase in plastic-plastic mating gears.

#### 4 CONCLUSIONS

In this study, the behaviors of plastic helical gears produced by 3D printers under different conditions were experimentally examined and the results are listed below.

Plastic helical gears are preferred over plastic spur gears in gear boxes and electric motors because they operate more quietly. To observe this, the test gears were loaded under different conditions, and the noise-emission values were measured. Compared to spur gears produced under the same conditions [25], the helical gears used in the study are approximately 5-10% quieter, and this difference is seen to increase with increasing load. At the same speed and torque values, it has been observed that speed is more effective in the noise-emission difference compared to torque, and it is consistent with the literature [25]. When the system is idle, the sound level of the test device is around 70 dB, and when loaded, it increases to around 100 dB. According to these differences in sound level, in future studies, wear-noise emission correlations can be established and wear behavior can be investigated without removing the gears from the system.

Gears produced in 3D printers have a very rough surface compared to other manufacturing techniques. The surface roughness values depend on the layer thickness determined when the parts are produced, and the layer thickness depends on the nozzle diameter, which enables manufacturing. Acceptable roughness values can be achieved by reducing the nozzle diameter; however, as the diameter decreases, the risk of the nozzle increases. It is not possible to obtain smooth and uniform layers with a clogged nozzle. As the layer thickness decreases, the hot end that melts the filament gets closer to the produced part and it becomes difficult for the layers to adhere together, causing a decrease in strength. Finally, as the layer thickness decreases, the production time of the part increases. For example, to produce a 0,2 mm thick part as 0,1 mm, two times more time is lost. Considering that the biggest disadvantage of 3D printers is the excessive production time, the extra time increase may reduce the use of this technique. In plastic-steel mating gears, surface roughness wears out rapidly and roughness values decrease depending on the rotation time. As the rotation times increase, the roughness values increase again. In future

studies, the service life of the gears can be examined by monitoring the increase in roughness values. Also surface roughness changes can be examined when rotating plastic-plastic mating depending on the load can be studied.

The disadvantage of plastic gears is that they can suddenly wear out and become unusable at high torque and speed. Replacing unusable gears causes significant loss in time. To prevent this, it is necessary to know the wear behavior and usage conditions of plastic gears. In the study, the system was rotated by  $10 \times 10^4$  at different loads and speeds to observe the wear on plastic helical gears. It was observed that when the load on the plastic gears increases, the amount of wear on the gears increases, and when the rotation speed of the gears increases, the wear decreases. Since the abrasive gear is steel, the system was operated at low speeds and torques in order for the gears to complete  $10 \times 10^4$  revolutions. Wear mechanisms at higher values can be examined in plastic-plastic gears, but compressed air should be used in this gear pair to prevent wear particles from sticking to each other and to prevent the temperature from melting the gears.

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