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Review: Failure Detection Method of Polymer Composite Gears

Hailemariam Nigus ¹

1 – Federal TVET Institute, Addis Ababa, Ethiopia

a – hailuqua@gmail.com



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Keywords: polymers, polymer gear, reinforced polymer composite gear, test rigs, test gear.

ABSTRACT. Polymer composite gears widely used these days as substitute material for steel gear in different load conditions and devices. Its failure mode differs from gears made of steel, thus it is important to categorize the failures shown by polymer composite gears. Several previous studies noted that wear detection, surface condition monitoring, weight loss and temperature detection can be used in detecting failure of polymer composite gear. Most pure polymer gears cannot with stand high temperature, the gear simply melts instead of creating crack. This article reviews the failure detection method mentioned above. Other researcher works were studied and their findings were extracted in order to identify the methods they used. The most common method used was wear detection, temperature detection and it was supplemented by other methods such as surface condition monitoring. Failures shown by polymer composite can be concluded to be tooth breakage, tooth deformation, material removal and surface fatigue. The review also concluded that the usage of reinforced polymer materials did a considerable improvement in polymer gears strength and performance.

Introduction. Polymers are giant organic molecules made up of hydrogen and carbon atoms with a series of repeating units connected to each other. The repeating structure molecules are called as monomers. Polymers are used in different devices like gears, Polymers gears are chosen to replace steel gear in low load devices due to the technical advantage and economic gains. The advantages of polymer gear is easy to operate with small amount of lubrication, light in weight material, clean environment and low operating noise [1] compared to metal gear. However, polymer materials suffer from poor mechanical strength and low thermal resistance [2] compared with composite polymer and metal gears.

Thermoplastic Polymer composites gears developed by adding fillers like Carbon fibers, glass fiber, silicon carbide and pozzolanic cement (PPC) are combined with polymer materials [5, 7, 19]. And plastic fiber resin and wound or molded it forms carbon fiber, glass fiber and silicon carbide reinforced plastics and Portland as filler material into the polypropylene matrix [7], which is extremely rigid, a very high strength-to weight and with very high heat withstanding and tolerance [3-4] of composite gears. Mao et.al. [20] has also discussed the detail fabrication of polymeric composite gears using various materials such as glass and carbon fiber reinforced Nylon 66 and Acetyl.

A wide variety of different types of polymer materials (PA, POM, etc.), different reinforcements (carbon fibers, glass fibers, nanoparticles, etc.) and internal lubricants (PTFE, MoS₂, etc.) can be used to tailor a polymer for a specific application. However, due to the large number of different materials available, it is very difficult to determine the optimal material combination for a specific gear drive, especially when also considering noise and vibration properties [14-18, 28, 31, and 34].

Natural materials also utilized to reinforced polymer composites gears to focus on the ecological recycling. Rice hull is a residual product of rice and it contains natural silica [5] describes by carbonized rice hull it gives Rice- Hull-Silica-Carbon (RHSC) with high strength and low frictional

of porous carbon material. The said research have used the RHSC as a reinforcing material in plastic gear.

Nonmetallic gear developed as an alternative to metallic gear because of their superior advantages on wear and fatigue characteristics (Duzcukoglu et al, 2009 [8], Hoskins et al., 2011 [9], Kirupasankar et al., 2012 [10] demonstrated that due to reinforcement, and residual compression stress in the tooth profile is more effectual in increasing the fatigue strength.

The load-carrying capacity, wear and fatigue life of gears are affected by many factors [1-3]. In the case of injection-molded plastic gear, the plastic materials and the bulk temperature are the most important factors [6]. The bulk temperature is easy to come close to the glass transition temperature of the plastic materials. Therefore, the plastic gears are added with reinforcing materials for keeping strength in high bulk temperature by improving heat resistance property.

Research emphasized on the effect of various parameters on the performance of the composite gear such as fiber length, gear tooth fillet radius, topography, fatigue and failure, tooth deflection, friction and wear etc.[11-14]. Few researchers determined the polymeric composite gear wear with respect to metallic gear by either bending strength or surface durability (Chauhan et al., 2010 [11]).

Gears are generally subjected to uni-directional cyclic loads; however, in applications like actuators of satellite launchers, gears experience bi-directional cyclic loads due to its rotation in both clockwise and counter clockwise directions [18]. Bidirectional and uni-directional bending fatigue performance of injection molded unreinforced and carbon fiber reinforced polyamide 66 gears were evaluated using a test rig [16-18, 29].

Composite gears of Acetyl, friction and wear performance were found to be entirely [26] dependent on surface temperature at high loads. The gear surface will wear slowly with a low specific wear rate if the gear is loaded below the critical value.

The composite gear material tested to evaluate its friction and wear characteristics in adhesive and abrasive wear modes. Weight loss due to wear of the composite gear is evaluated through direct measurement under a specific load and running condition. This is because shear strength and surface energy of the composite material changes while toughness and hardness of the material improves due to strengthening by cement fillers [7].

Polymer gear failures are different from steel and polymer composites because of the material properties of polymer are totally different from the two. An example of polymer gear failure is melting of material which does not occur for steel gears and polymer composites. This type of failure can be categorized under thermal damage [6, 7, 13, 23-27].

In this articles review influence of reinforcement on the wear resistance, hardness of polymer gears, surface temperature and tribological property is well discussed.

Experiments

Test gear. To determine the strength of polymer based gears using nylon materials of different grades, test gears were developed. Different condition monitoring techniques for polymer-based gears are considered [14] for use in gear tests. The tests gears available uses Nylon (30% glass filled) with 25% Sic, Nylon 6 with 25% Sic, Nylon 66 with 25% Sic. This material were utilized in producing these gears using injection molding, fig 1 shows the injection molding machine. Based on [4] mentioned composition ratios gears of various reinforced materials were made as depicted in fig 2, 3, &4. In the process of testing, test polymer based gear was mated against the hobbled standard metal spur gear [25-27].



Fig. 1. Injection molding machine [4].



Fig. 3. Nylon 6 + Sic [4].



Fig. 3. Nylon 66 + Sic [4].



Fig. 4. Nylon (GF) + Sic [4].

Similarly, test gears made from polyacetal copolymer (POM) and the composite materials of POM and RHSC-particle were also developed [15]. These were made in order test the strength of poly acetyl copolymer based gears. The dopant ratio and median grain diameters of RHSC-particle are shown Table 1.

Table 1. Material for test gears [5].

Material	POM	RHSC5	RHSC60
Matrix	Polyacetal		
Filler	—	RHSC particle	
Median grain diameter [μm]	—	5	60
Dopant ratio wt. %	—	7	

Unreinforced polyamide 66 (PA) and 20 wt. % and long carbon fiber reinforced polyamide 66 (PACF) were utilized prepared by injection molding for the said test gears [18, 21, and 25] as shown in fig. 5.

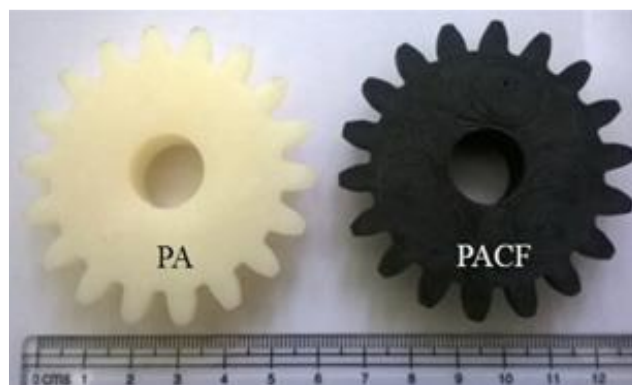


Fig. 5. View of injection molded unreinforced and reinforced polyamide Gears [18].

Experimental test rig. Test gears were subjected to some experimental test to measure its strength and durability under different parameters such as: rotational speed, torque, and temperature. This

done with the use of experimental test rig. In gear tooth surface temperature test, temperature test uses non-contact infrared temperature sensors to indicate significant variation in gear temperature depending upon the torque transmitted, operating speed and material properties [13]. The schematic representations of this experimental apparatus as shown in Fig.6 and Fig.7 are used to measure different parameters such as rotational speed, torque and temperature for the test gears types. The synchronous speed of the motor can be set at random within the range from 300 to 1800 rpm and the rotational speed of test gear is monitored by a tachometer. To set up the testing torque, a torque meter and a powder brake were added to this equipment. During the experiment, the bulk temperature of test gear was measured by a radiation thermometer [5].

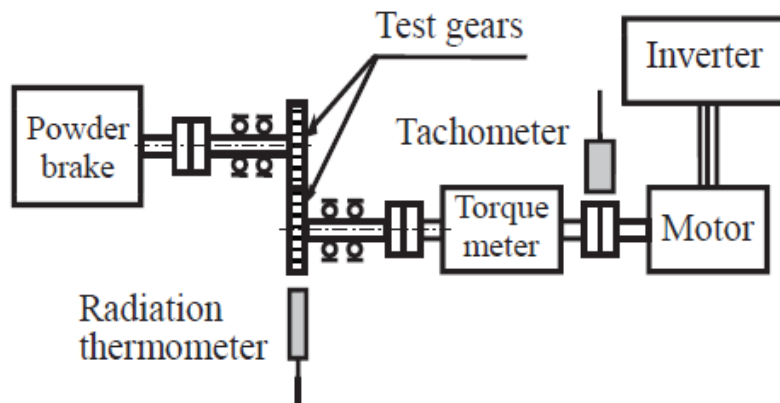


Fig. 6. Experimental apparatus and measuring system.

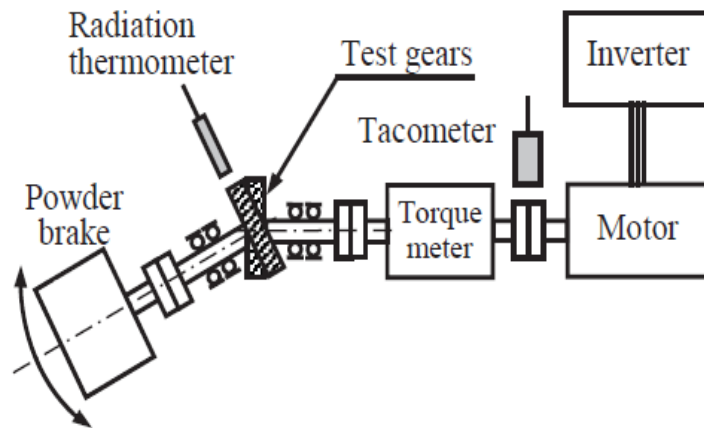


Fig. 7. Experimental apparatus and measuring system for spur gear pair and helical gear [5] crossed helical gears [5].

Test rig also used evaluating the bending fatigue performance of polymer composite gears. The entire system consisting of loading system, control panel, thermal camera and data acquisition, is shown in Fig. 8. The picture shown in Fig. 9 is the close-up view of test rig consists of driving and driven shafts which were suitably supported between bearings at a desired center distance.



Fig. 8. In-house developed gear test rig [18].

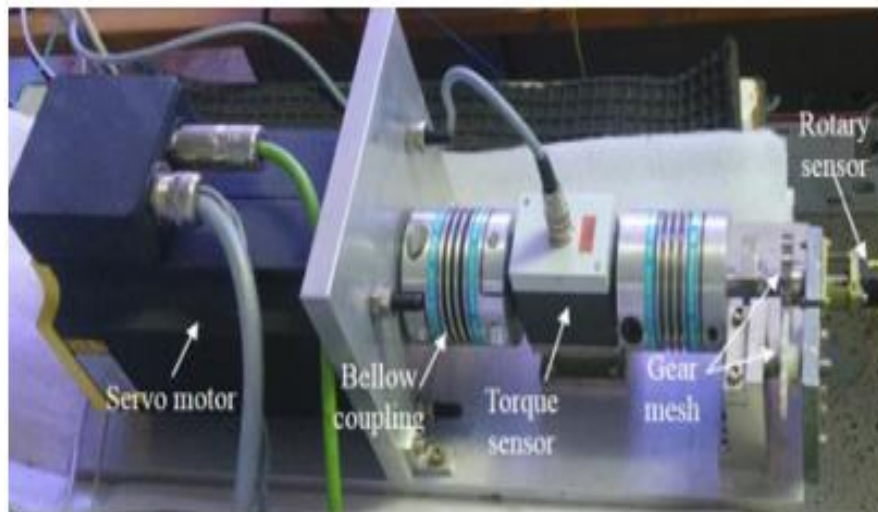


Fig. 9. Gear test rig (close-up view) [18].

Polymer composite gears can be tested in much the same way as metal gears, using a back to back test configuration where the gears are loaded by winding in the torque to a prescribed level (Fig. 10) [27]. The main difference in the design of this rig is that the bearing block locating the test gears was made to pivot, with the gears loaded by a moment arm and adjustable weight. The arrangement is shown in Fig 10.

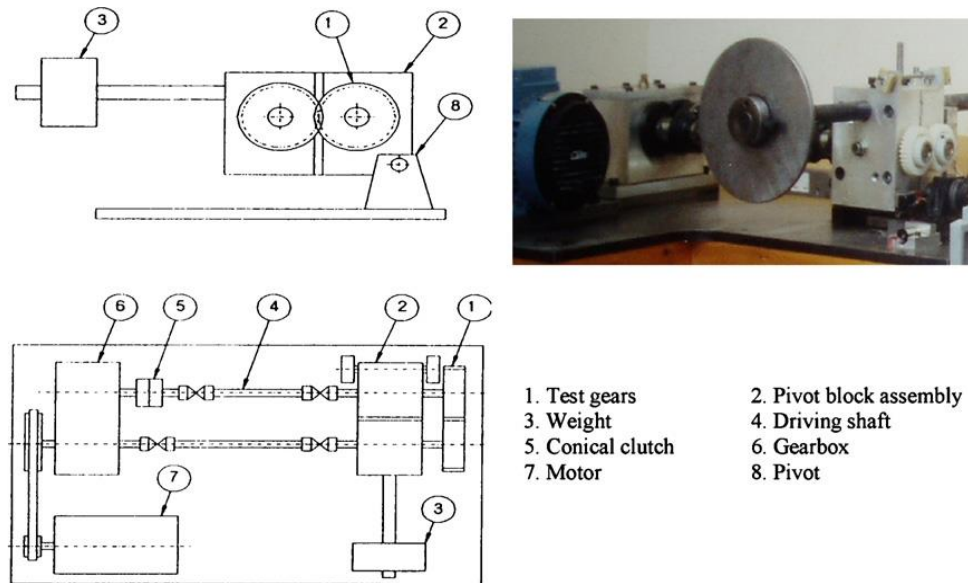


Fig. 10. Test rig for polymer gears. [27].

The composite test gears are subjected to the dynamic test and wear loss is evaluated by weight loss measurement [7, 16]. The photographs of intact tooth profile and tooth profile after test have been given in the figure 11& figure 12.

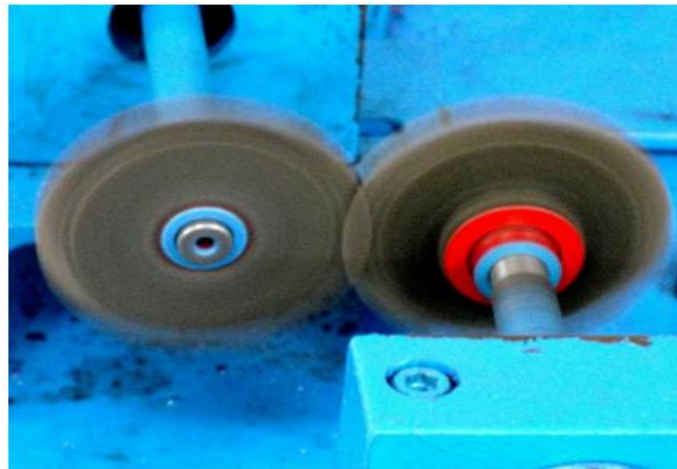


Fig. 11. Gear pair meshing at dynamic condition [7].

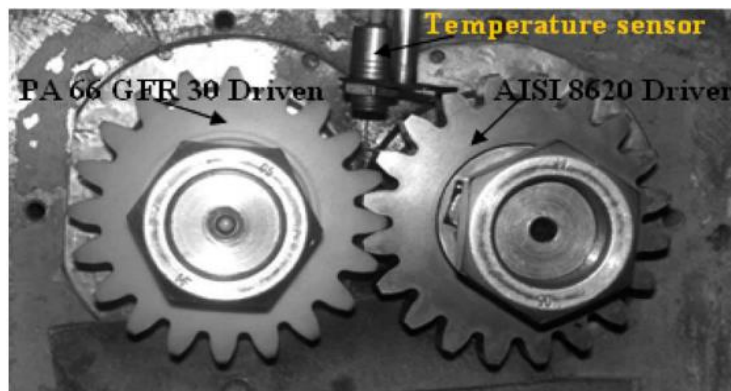


Fig. 12. Measurement of a tooth temperature [16].

The Pin on Disc machine can also consider as test rig which is used to evaluate the wear and friction characteristics as depicted in fig 13. The sliding friction test occurs between a stationary pin stylus and a rotating disk. Normal load, rotational speed, and wear track diameter can be varied [13]. Electronic sensors monitor wear and the tangential force of friction as a function of load, speed, lubrication, or environmental condition [5].



Fig. 13. Pin on Disc setup [4].

Result and discussion.

Wear evaluation and surface pitting. The results from pin on disc testing which was done to study the wear behavior and pitting of the polymer composite materials showed that surface hardness is higher and wear was less in Nylon 66 material when compared to other test gears [4] as shown in table 2.

Table 2. Test results of wear and hardness [4].

Description	Nylon 6 + 25% Sic	Nylon66 + 25% Sic	Nylon with(30% Glass Filled) + Sic
WEAR loss in mg	0.00175	0.00125	0.00118
HARDNESS in shore 'D'	68	72	64

Bulk temperature. Gear surface temperatures were measured during running using an infra-red video camera [17, 20]. The picture on Fig. 14 shows an image of the running gears and the temperature changes across the face width as well as circumferentially around the gears using this method.



Fig. 14. Surface temperature measurements [17, 20].

The bulk temperature of RHSC gear discusses in [5] increases over time and reaches equilibrium as shown in fig.15. However, the bulk temperature of POM rapidly increases after the start of rotation, peaks, and then decreases gradually, reaches equilibrium, Fig 16 shows also when the test gear is helical.

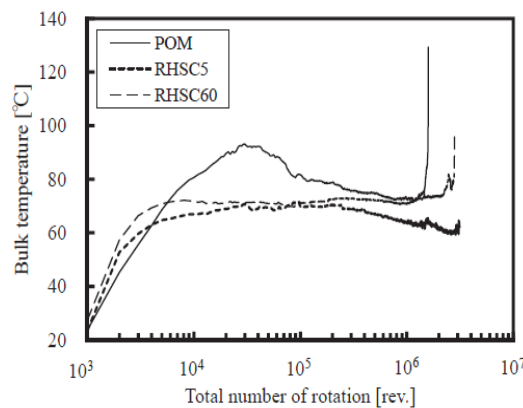


Fig. 15. Spur gear pair, Torque 3.0 Nm [5]

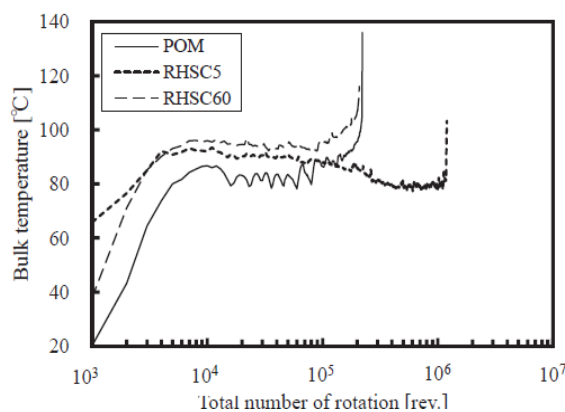


Fig. 16. Helical gear pair, Torque 3.5 Nm [5]

The surface temperature in reinforced gear is less compared with the unreinforced polymer gear [14] due to high thermal conductivity of the glass filled nylon also contributes to increased heat dissipation as shown in fig 17.

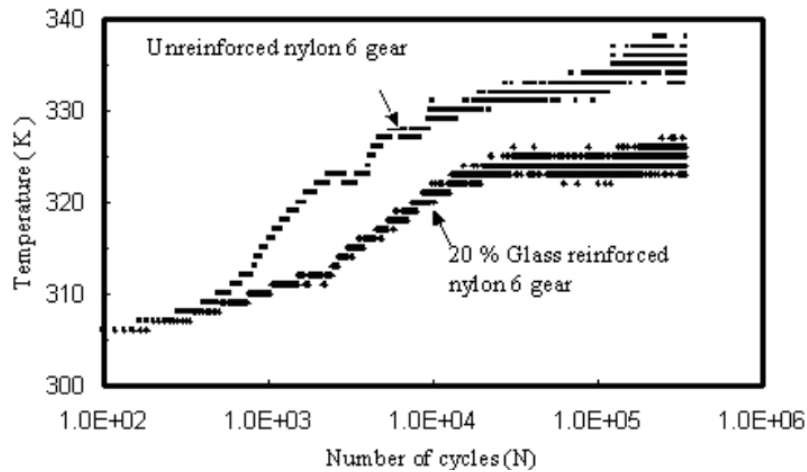


Fig. 17. Gear tooth surface temperature of unreinforced and glass reinforced gear [14].

The enhancement in mechanical properties of polyamide nano composite gears results in higher power transmission efficiency compared to unreinforced polyamide gears [21]. The surface temperature of reinforced polymers compared with pure polymers discussed in [16, 18, 29], Fig. 18 shows the net surface temperature of PA and PACF gears subjected to 8.5 Nm loads, Temperature rise of PACF gears was about 84% lesser than that of PA gears subjected to bi-directional loads [18]. It can also be seen that temperature rise in PA gear under bi-directional load was higher than uni-directional load as shown in figure 19.

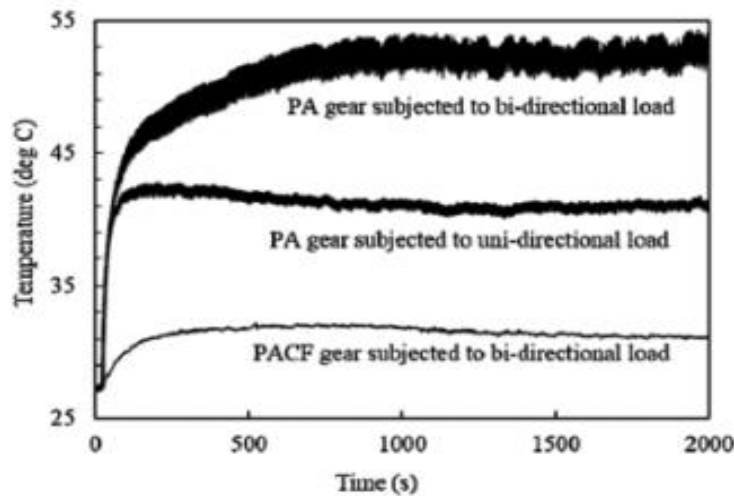


Fig. 18. Surface temperatures of PA and PACF gears [18].

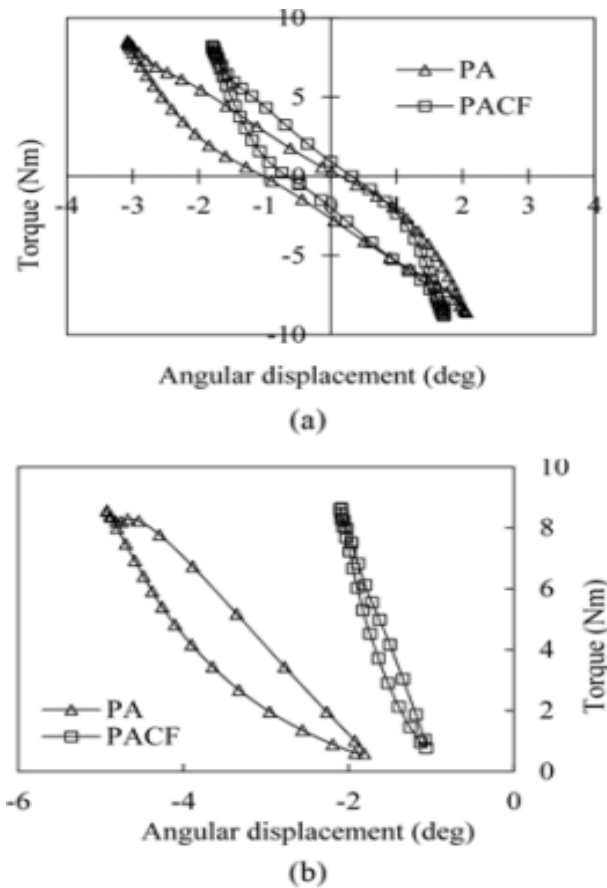


Fig. 19. (a) Hysteresis loops of PA and PACF gears subjected to bidirectional load, (b) Hysteresis loops of PA and PACF gears subjected to uni-directional 8.5 Nm loads [18].

Fatigue life. Gear fail mode can be avoided by using an appropriate material pair. Fatigue can be measured by life span tests and is predictable. However, the melting of pure polymer gears, which is a consequence of high gear temperatures, is not easily predictable. For reliable and optimal gear design, gear testing cannot be avoided because the tribological interaction between gears is specific for each combination of materials [30]. Reinforced gears exhibited longer life compared with unreinforced gears due to their superior mechanical strength and thermal resistance [23]. Mao [27] performed extensive testing of different gear geometries, loads and with different material combinations.

Plastic gears are affected by heat; the average value of the gear bulk temperature during operation was used as an index to evaluate the fatigue life. The average bulk temperature represents the amount of fatigue work to the test gears during operation. Figure 20 and figure 21 represents the fatigue life by temperature index of composite gears and pure polymer gears [5].

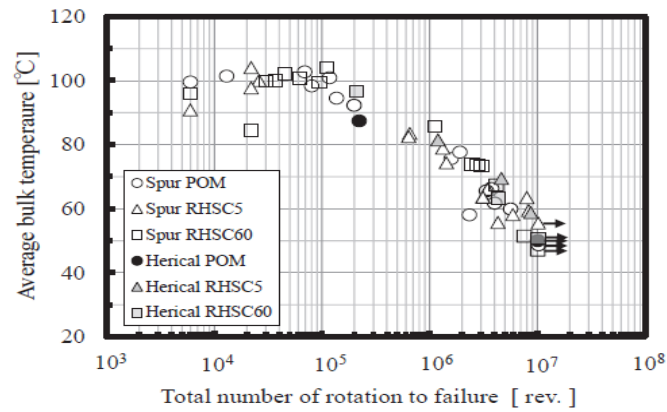


Fig. 20. Bulk temperature and fatigue life (Spur gear pair and helical gear pair) [5].

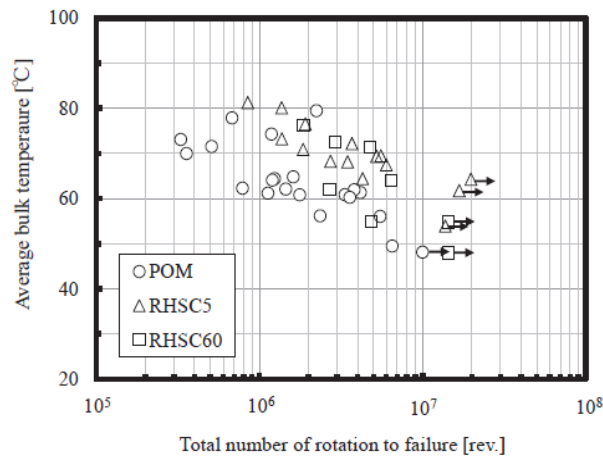


Fig. 21. Bulk temperature and fatigue life (Crossed helical gears) [5].

Failure mode of composite gears. Several damage mechanisms can occur on polymer gears according to the literature. The main ones are excessive tooth wear, fatigue (tooth cracking) and tooth deformation [27, 23].

The failure mechanism depends on the testing conditions (load, speed and temperature) and material combination [23]. Surface cracks were dominant in unreinforced gears subjected to low stresses. Severe deformation was observed at higher stress levels.

Wear rate also the predominate form of failure for polyacetal (POM) gears, especially above critical loads [27]. Other specific research was performed with the goal of better understanding gear rolling sliding contact [32] and gear durability [16]. The damage forms of composite and pure polymer gears are shown in Fig. 22 and Fig.23. In the case of spur gear pair, POM was melted for the frictional heat. However, RHSC-gear was breakage [5]. The damage forms differ in existence of the RHSC particle. Also, the damage forms of helical gear pair are approximately equal to the case of spur gear pair [5, 22-24].

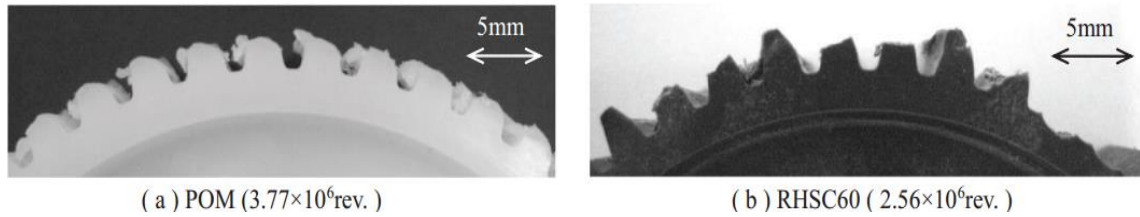


Fig. 22. Damage forms of spur gear (Torque 3.0 Nm) [5].

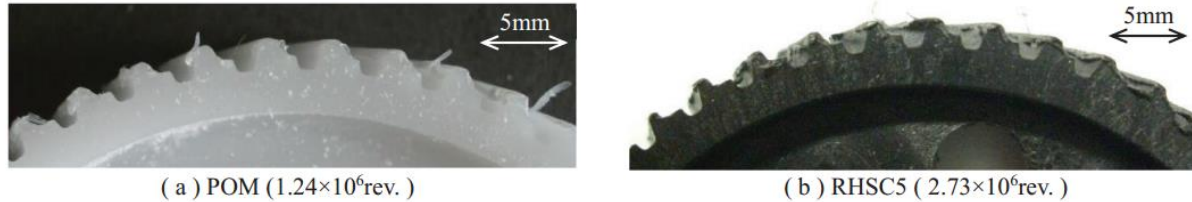


Fig. 23. Damage forms of crossed helical gears (Torque 0.5 Nm, Rotational speed 500 rpm) [5].

The failure mode in figure 24 (a-f) shows different loading conditions of pure polymer with different applied loads (uni directional and bi-directional) and angular speeds [18]

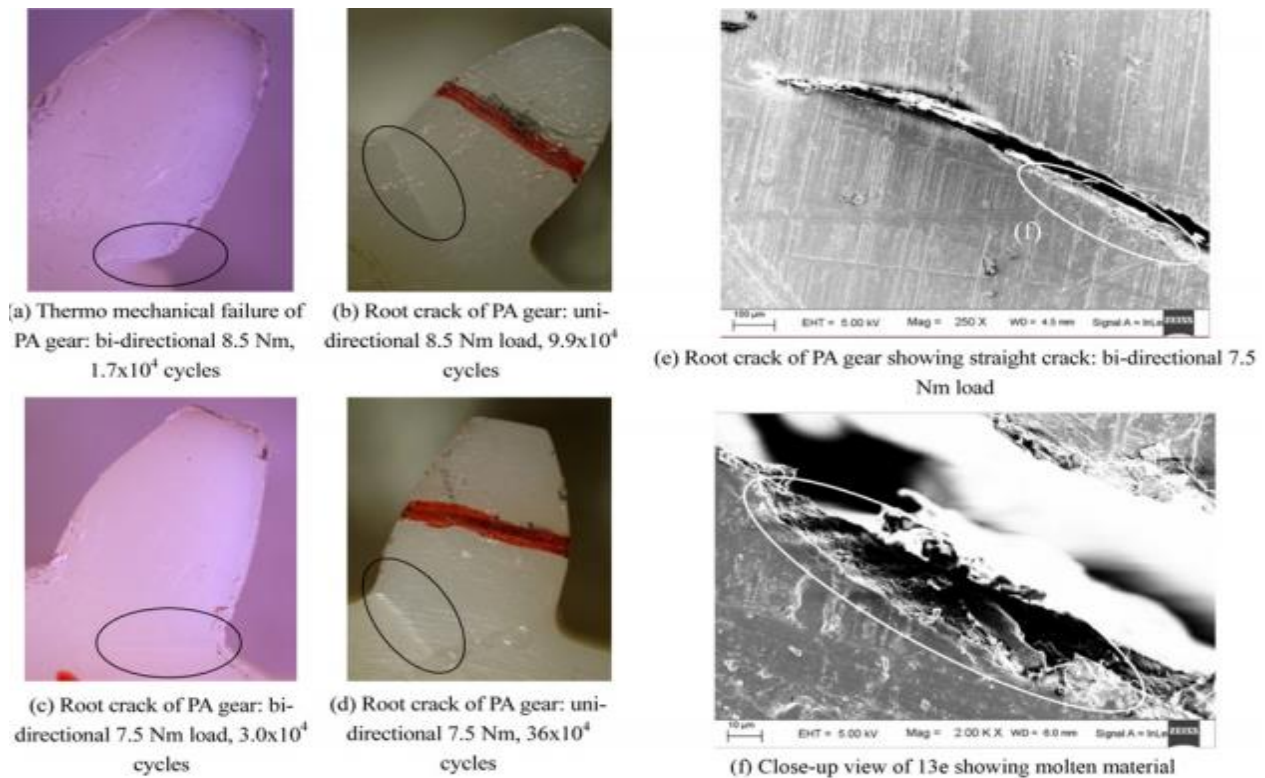


Fig. 24. Failure modes of PA gears [18].

Regarding, reinforced fibers are generally orient along the melt flow and boundary of the cavity. Due to the presence of reinforced fibers in the direction of crack growth, tortuous nature of path was observed on PACF gear tooth. (Figs. 25(a-d)) when subjected to both uni-directional and bi-directional loads fiber pull-out and matrix separation. Thus, both bi-directional and unidirectional loads generated similar failure in the PACF gear [18].

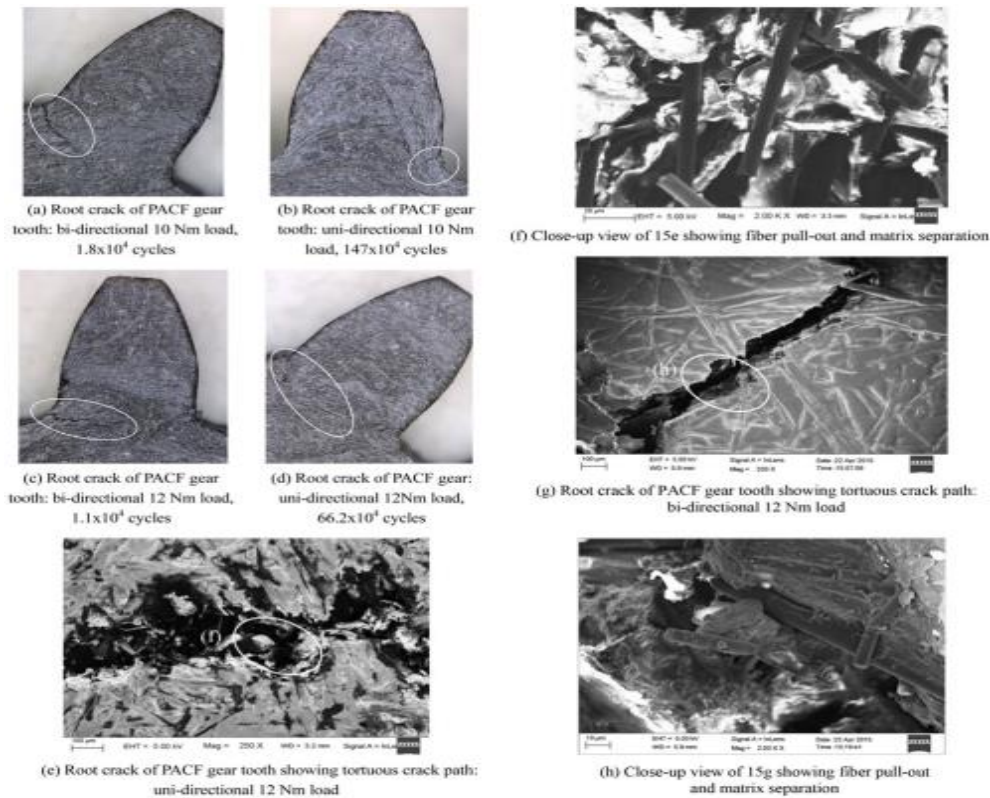


Fig. 25. Failure modes of PACF gears [18].

Tooth surface. The coefficient of friction of composite materials and pure polymer gears were tested [7] in different loading conditions as a result the reinforced polymer shows less coefficient of friction as depicted in fig 26 and 27.

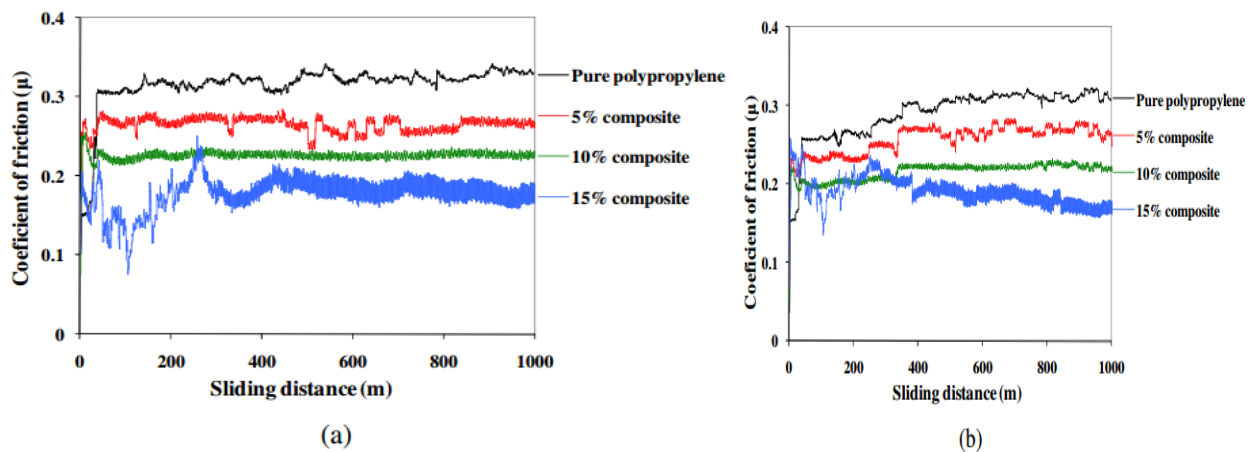


Fig. 26. Coefficient of friction evaluated for an applied load (a) 19.6 and (b) 29.4 N [7].

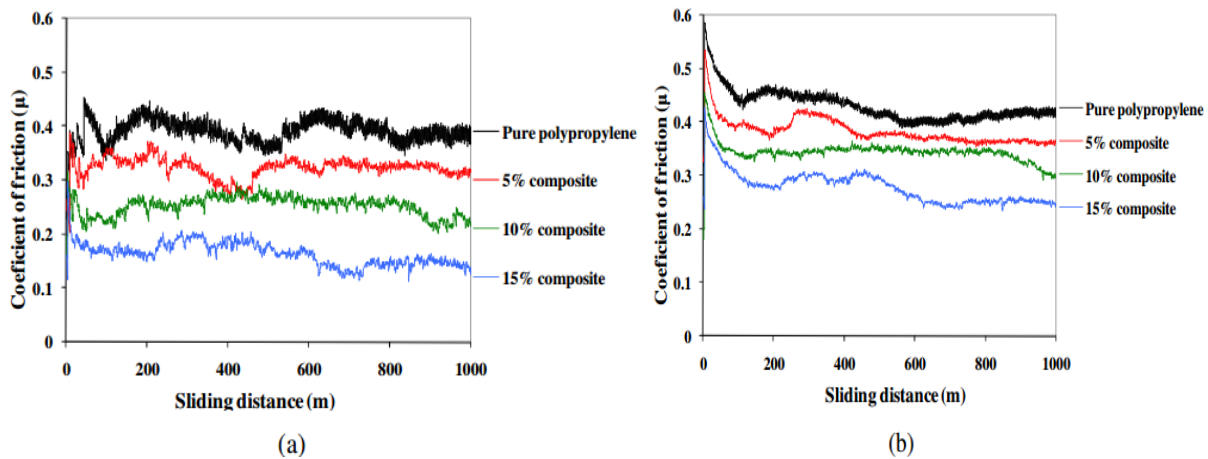


Fig. 27. Coefficient of friction on abrasive mode under applied load (a) 9.8 N and (b) 19.6 [7].

The influence of normal load and sliding velocity, coefficient of friction and specific wear rate is plotted against two different applied normal loads during wear test. The coefficient of friction, of all the gear materials for adhesive and abrasive wear properties, decreased with increase in normal load as shown in Figure 28 and Figure 29. Further, it is observed that under same loading conditions, PPC reinforced composite gear materials exhibit less specific wear rate than unreinforced polypropylene, comparable to abrasive wear as well. The same trend has also demonstrated in the Figure 29. It is observed that 10% cement filled composite material exhibits less specific wear rate than pure polypropylene.

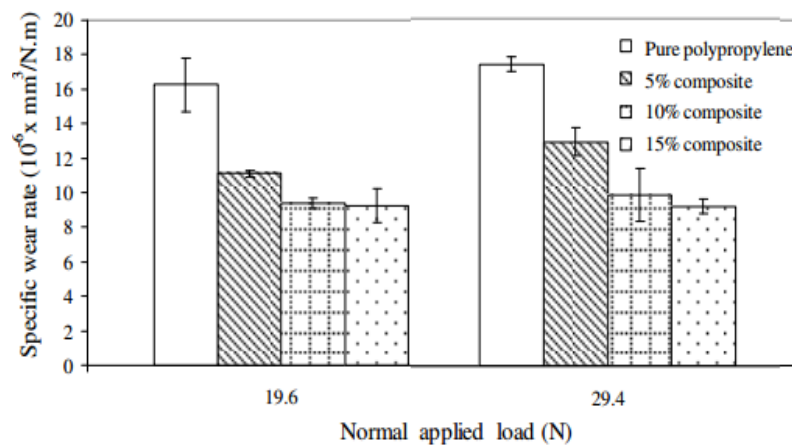


Fig. 28. Specific wear rate with applied Normal load in adhesive wear.

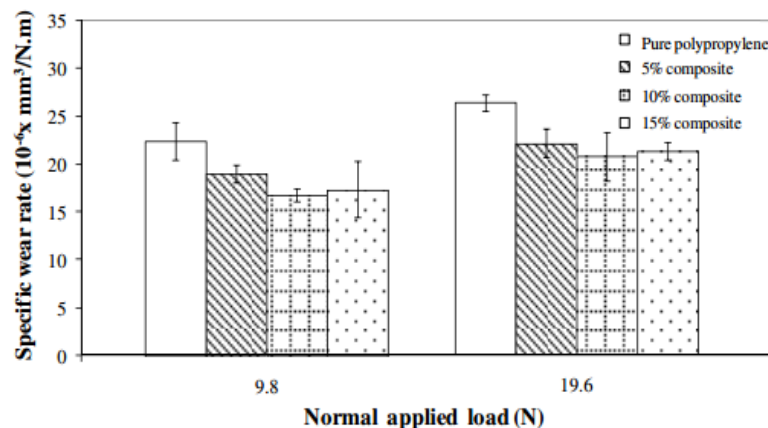


Fig. 29. Specific wear rate with applied normal load in abrasive wear [7].

From both intact edge profile and edge profile after test, are taken into account, and the weight loss due to wear and wear volume have been calculated for all the samples for two variable loading conditions i.e. 13.5 N and 8.5 N. The graphical expressions for both the cases are highlighted in the Figures 30-31 and Figures 32-33 respectively. Weight loss due to wear and wear volume of pure polypropylene gear is showing the highest value at elevated rpm. At 2500 rpm, both the parameters, weight loss due to wear and wear volume are highest in comparison with other running speeds. The reason is that the engaged tooth pair comes in contact more frequently when the running speed is 2500 rpm as compared to other variable speeds. Due to repeated contact, more friction takes place between the common tooth pair with less time as compared to other speeds.

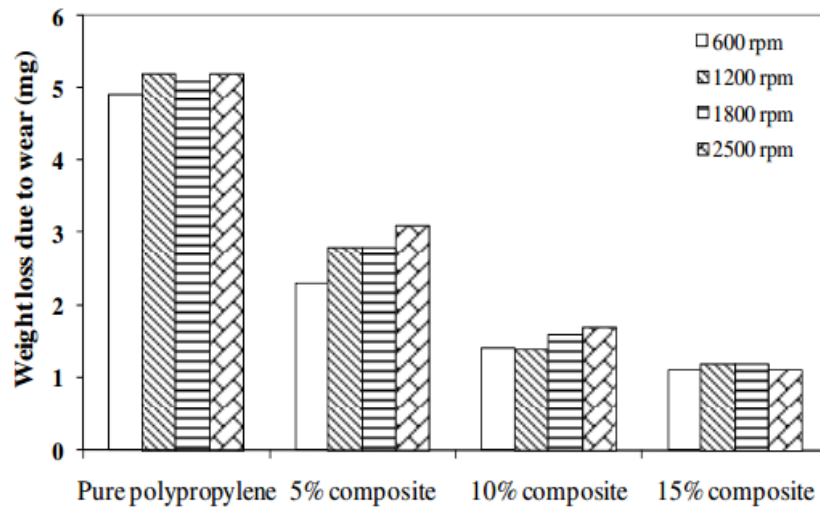


Fig. 30. Weight losses due to wear at different rpm with 13.5 N loads [7].

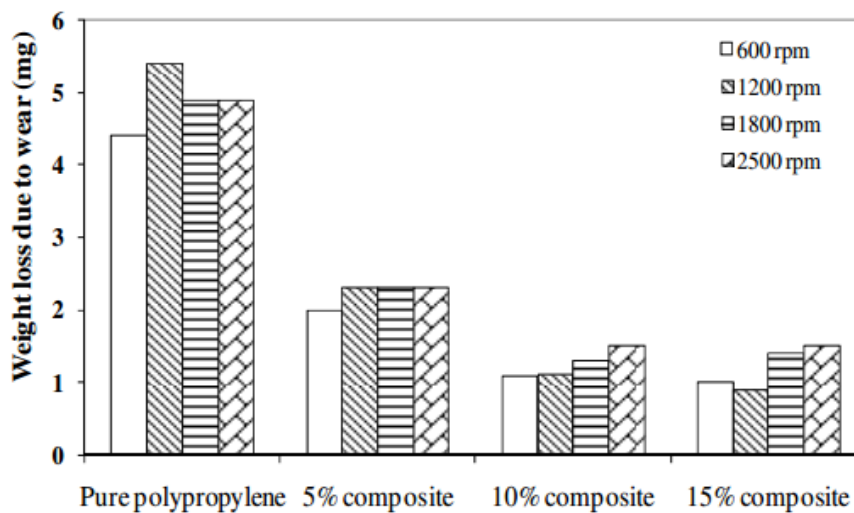


Fig. 31. Weight losses due to wear at different rpm with 8.5 N loads [7].

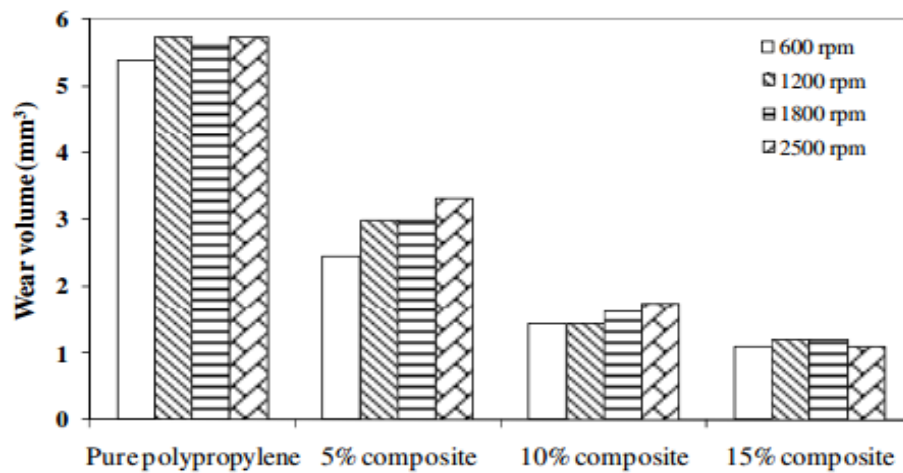


Fig. 32. Wear volume at different rpm with 13.5 N loads [7].

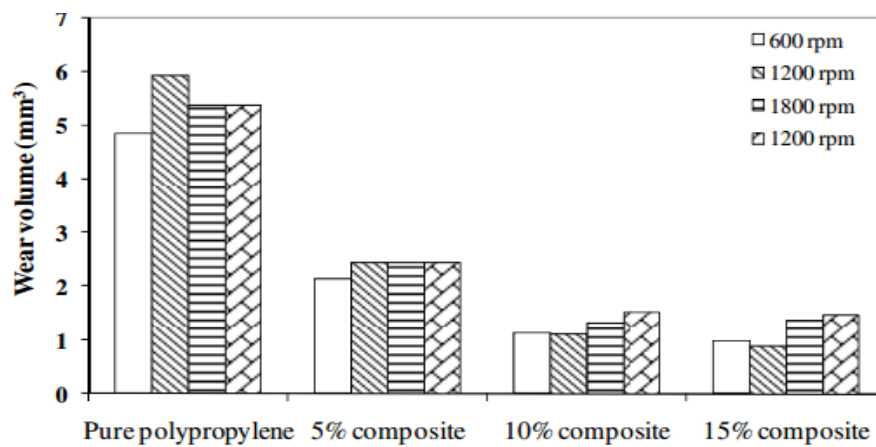


Fig. 33. Wear volume at different rpm with 8.5 N load [7].

Influence of reinforcement on gear efficiency. Providing unreinforced materials on gear molding has mattered on its efficiency. Reinforced gears exhibit less tooth deflection than unreinforced ones for the same loading condition due to the superior material modulus [22, 24]. During testing, repeated gear tooth deflection and material hysteresis contribute to an increase in gear temperature. [21] Discussed an increase in torque increases the gear pair efficiency, as shown in Figs. 34 and 35.

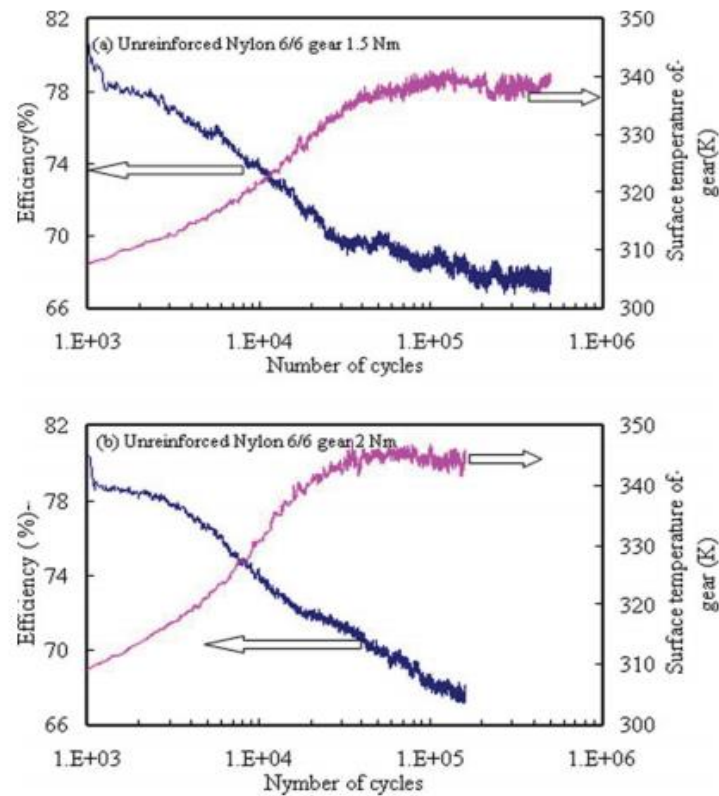


Fig. 34. Efficiency of unreinforced nylon 6/6 gears tested at (a) 1.5 Nm torque and 1000 r/min and (b) 2 Nm torque and 1000 r/min [21].

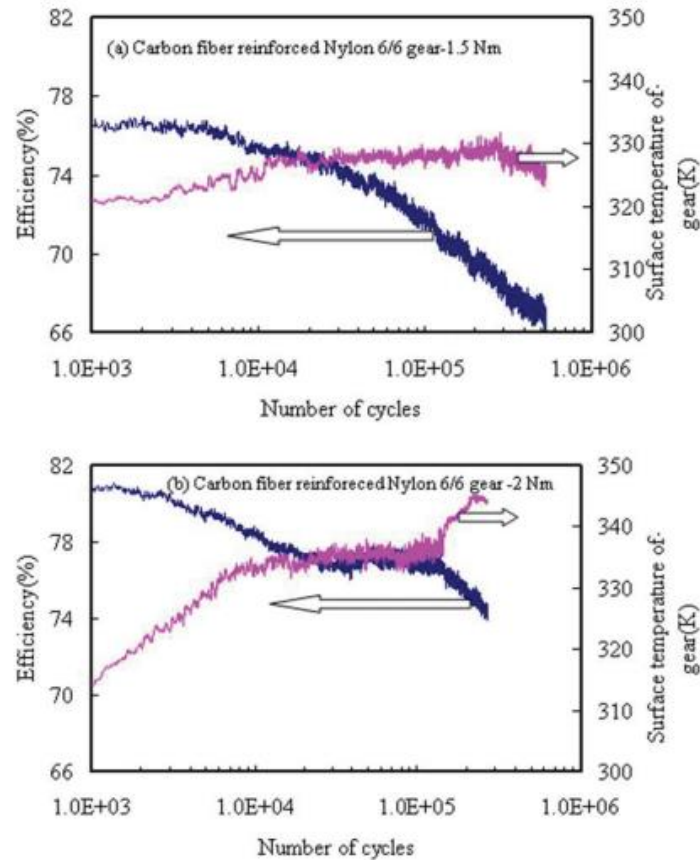


Fig. 35. Efficiency of carbon-fiber-reinforced nylon 6/6 gears tested at (a) 1.5 Nm torque and 1000 r/min and (b) 2 Nm torque and 1000 r/min [21].

Summary. Hence, it can be effectively concluded that the usage of polymer material and the addition of reinforced material did considerably improve the polymer gears strength and performance.

The advantage of using composite gears is the inability of metals and their alloys in meeting today's gears requirements. The composite which has carbon fiber matrices has better mechanical properties, higher specific strength (strength to density ratio), higher specific modulus, and better fatigue and wear resistance compared to metals. It has also higher specific energy absorption, which is imperative in low load gear design, due to the fact that it will reduce weight, cost, noise and vibrations. Moreover, polymeric matrix composites (PMC) have limited transmission gearing and low loading abilities. The polymer composite gears and pure polymer gear failure mode is different. Polymer composite gear failure can be wear or fatigue. Fatigue can be measured directly by life tests, but wear needs to be continuously recorded by test rigs.

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