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Durability of Polymer Gear-Paired with Steel Gear Manufactured by Wire Cut Electric Discharge Machining and Hobbing

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In the recent years, utilization of non-standard gears have increased due to the improved load carrying capacity and improved durability. However, these non standard gears are manufactured by non-conventional manufacturing process including wire cut electric discharging machining (WEDM). Standard gears are manufactured by conventional machining process, hobbing. This work reported the performance of injection molded polymer gear paired with a steel gear manufactured by conventional hobbing and wire cut electric discharge machining process. WEDM steel gear surface exhibited poor surface topology and higher hardness when compared to that of conventional machined steel gear. Measured net surface temperature of polymer gear at various loads (2-3 Nm) confirmed a temperature rise of 10-15°C when paired with WEDM gear compared to that of hobbed and ground gear. Polymer gear paired with WEDM exhibited inferior fatigue performance when compared to the polymer gear paired with hobbed and ground gear.

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1. Introduction

Enhancement of gear performance is being attempted for many years due to the extensive utilization of gears in many applications. Extensive investigations have been carried in the domain of gear materials, gear design and gear manufacturing. Polymer based gears are preferred over metal gears due to its technical and economical advantages. In general, polymer gears are in mesh with a steel pinion to avoid thermo mechanical fatigue failure and to limit the size of the pinion gear. One such application is windshield wiper drive mechanism in an automobile. When gears are utilized for power/motion transmission, considerable amount of heat is generated due to the material hysteresis and surface interaction. If both pinion and gears are made of polymeric material, then the generated heat will not be easily dissipated due to its poor thermal conductivity characteristics. In the recent years, non standard gears including asymmetric gears (having different pressure angle at drive side and coast side) have drawn researchers' attention due to the advent of new manufacturing processes. Polymer based materials are conveniently used to manufacture non standard gears through injection molding as it involves only one complex profile die. These non standard polymer gears are generally paired with identical steel pinion due to the requirement of superior load carrying capacity. Thus, standard polymer gears will be meshed with a hobbed steel gear, whereas non-standard polymer gears will be in mesh with a WEDM steel gear. For the comprehensive understanding of non standard gears, there is a need to understand the effect of mating steel gear manufacturing process.

Few researchers have investigated the effect of manufacturing processes over gear performance.[1-8] Bergseth et al.[1] manufactured gears by hobbing, green-shaving, honing and grinding and investigated the influence of surface topography on the contact area and pressure using boundary element method. Green shaved gear and honed gear exhibited the highest contact area ratio. Real surface topography significantly affects wear, friction and lubrication properties of the contact. Gupta and Jain[2] manufactured miniature gears by WEDM and studied surface topography, bearing length parameters, microstructure and micro hardness. At low discharge energy parameters, manufactured gear exhibited less profile and lead deviation with less surface roughness. Akkurt[3] investigated the performance of acetal gears when meshed with a steel gear having various surface roughnesses. Wear rate as well as wear mechanism were influenced by the surface roughness of the steel gear. Moorthy and Shaw[4] investigated the contact fatigue performance of grounded and coated gears. Coated gears exhibited superior resistance against pitting damage when compare to that of ground gears. Nakatsuji and Mori[5] examined surface durability of electrolytic polished gears and ground gears of same surface roughness. Electroylitc polishing generates micro pores which create lubricating films between the tooth surfaces and enhance resistance against pitting. Tung and Cheng[6] experimentally simulated the grease lubricated polymer- steel worm gear interface with the aid of pin on disc tribometer. Kim et al.[7] evaluated the performance of steel worm gear meshed with nylon 6 worm wheel. The efficiency of the worm gear found to increase with the increase in load due to the adhesion shearing theory. Ali et al.[8] manufactured miniature gears through micro WEDM and conventional WEDM. The average surface roughness of micro EDM and conventional WEDM are found to be 50 nm and 2 μm. The range of dimensional accuracy exhibited by the micro EDM and conventional WEDM are 0.1~1 μm and 2~3 μm respectively.

Few research investigations[9-13] have been carried out to understand the friction wear performance of polymer against steel surface. Wieleb[9] investigated the tribological performance of PTFE composites against steel counter faces with different roughness under dry conditions. The coefficient of friction and wear rate were found to be significantly influenced by the surface roughness parameter including asperity shape. Barrett et al.[10] investigated the influence of mating surface roughness over the friction wear performance of ultra-high molecular weight polyethylene using pin on disc configuration. An increase in coefficient of friction was observed at higher surface roughness for all the investigated sliding speed. Hohn et al.[11] considered different surfaces of disc including circumferential grinding, transverse grinding, transverse structured and evaluated mean film thickness and pressure distribution with the aid of FZG twin disc test rig. The contact pressure found to increase with increase in surface roughness of the counter disc. Frankile and Kraker[12] investigated the effect surface topography on the wear of POM-PTFE composite. The roughness of the steel counter face was varied in the range of 0.01-0.70 µm using grinding and grit blasting. Transfer layer formed on steel surfaces depend on the surface roughness height and roughness orientation. Ovaert and Ramachandra[13] investigated the effect of counter face topography on PAI and HDPE polymers wear. Oriented scribing patterns were generated on the counter face. A stable and well adhered polymer transfer film was formed at lower surface roughness disc whereas unstable polymer layer was formed at higher surface roughness disc.

Few works[14-16] have been carried out to understand the effect of electric discharge machining over surface and mechanical properties. Kumar et al.[14] reviewed the phenomenon of surface modification by electric discharge machining (EDM) process. Surface layer produced by EDM contains a top white layer which crystallizes from the liquid cooled at high speed. White layers generated on a steel workpiece have higher carbon content which resulted in increased resistance to abrasion and corrosion. Llanes et al.[15] investigated the influence of surface finish by EDM on the flexural strength for tungsten carbide based materials. Four point bending test was carried out and compared with conventional grinding and polishing process. From the investigation it was concluded that the flexural strength of material reduced due to EDM-induced flaws including surface residual stress. Bonny et al.[16] prepared ZrO_2 based composites surface by wire cut electric discharge machining and polishing to evaluate tribological performance. The coefficient of friction and wear rate of a composite machined by the WEDM were found to be higher when compared to that of the polished composite.

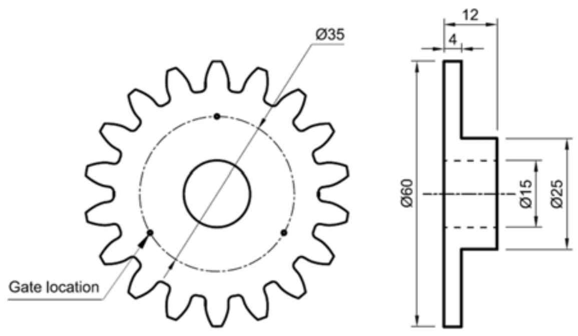

Fig. 1 Test gear major dimension

Table 1 Test gear major parameters

Parameters	Test & Mating Gear
Pressure angle (°)	20
Module (mm)	3
Number of teeth	18
Pitch circle diameter (mm)	54
Face width (mm)	4 & 12
Root fillet radius (mm)	1.14

From the summary of the literature review, it is observed that the surface condition of test gear significantly affect the surface durability of the gears. Friction and wear performance of the polymer based material is significantly affected by the counter surface topology. WEDM process alters the surface properties. No investigation was carried out to understand the surface durability of polymer gears against conventional machined and WEDM gear and this work attempts the same.

2. Material, Manufacturing and Methodology

Engineering polymer, polypropylene (M110 Haldia Petrochemical Ltd.,) was considered for gear material due to its superior fatigue life combined with low density. Materials were dried at 353 K for 4 h before injection molding to remove the moisture content. Gear details are shown in Fig. 1 and Table 1. Considered material was injection molded (Texair, JTS 40) to spur gears. Injection pressure of 9 MPa was used and temperature maintained in three zones of the barrel was 483, 503 and 523 K.

Durability evaluation of injection molded polypropylene (PP) gears was carried out with the aid power absorption test rig developed in-house (Fig. 2(a)). Schematic of power transmission between steel and polymer gear is shown in Fig. 2(b). Test polymer gear performance was evaluated by pairing with standard stainless steel gears manufactured by conventional machining and WEDM process. Brass wire electrode was used for manufacturing stainless steel WEDM gear. Injection molded polymer gears and steel gears were measured for its accuracy (NILES Gear Measuring System) with the support of Perfect Gears

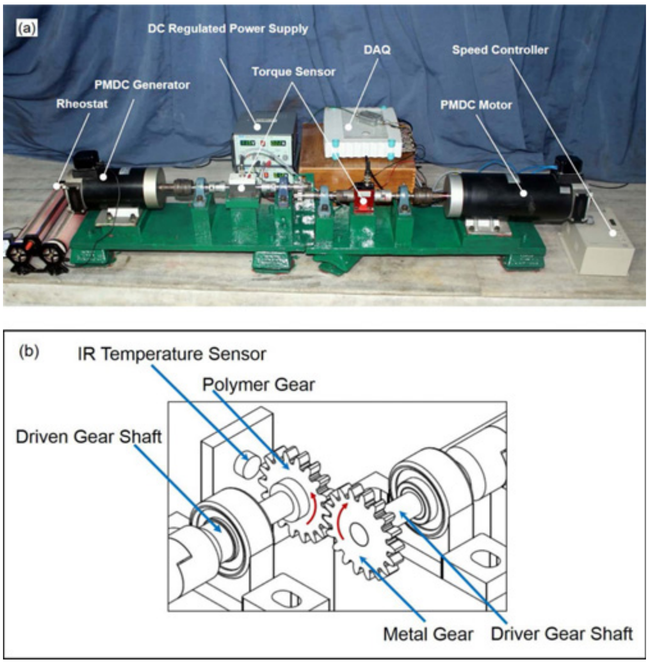

Fig. 2 (a) In-house developed power absorption gear test rig, (b) Schematic of power transmission between polymer and metal gear

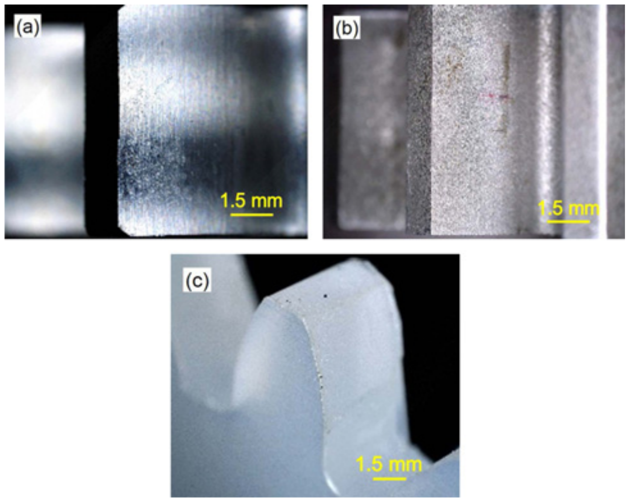

Fig. 3 Mating gear tooth surface manufactured by (a) conventional machining and (b) wire-cut electric discharge machining. (c) Injection molded polypropylene gear showing tooth profile

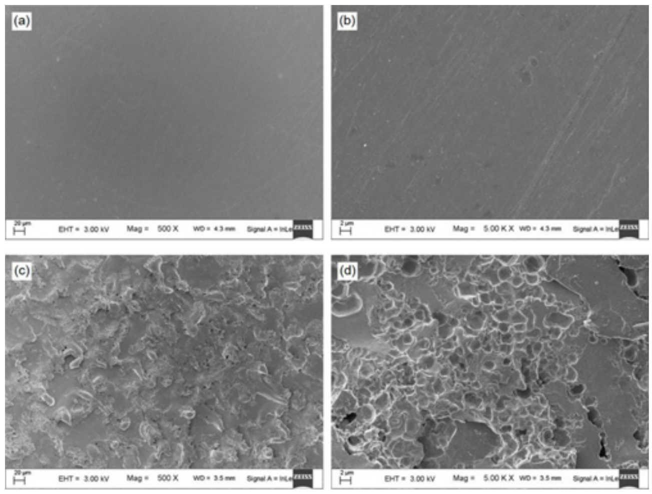

Fig. 4 Scanning electron micrographs of gear tooth surface manufactured by (a)~(b) conventional machining and (c)~(d) wire-cut electric discharge machining

Chennai, India. Injection molded gears are of DIN quality 10, WEDM and machined steel gears are of DIN quality 8 and 5 respectively. Polymer gear was paired with steel gear having larger face width, so that under any misalignment condition, the hard steel gear edge cannot contact and causes damage to the soft polymer gears. Test gear was connected to a permanent magnet direct current (PMDC) generator (1 kW) meshed with identical standard metallic gear (SS 316). The standard steel gear was manufactured by hobbing followed by grounding (conventional machining) and wire cut electric discharge machining (WEDM) process. Mating steel gear tooth surface was observed under scanning electron microscope (Zeiss Sigma), non-contact three dimensional profiler (Taylor Hobson CCI MP) to understand its surface topology. Presence of elements on the manufactured mating steel gear tooth surfaces was confirmed using XRD (PANalytical). The micro hardness of the mating steel gear tooth surface was measured (Buehler 1600) to understand its frictional characteristics.

Standard steel gear was driven by the PMDC motor (1.5 kW) and could be run at any speed up to 1500 r/min. Test gears were loaded by generator through rheostat. The torque available at both the drive and driven side were measured with in-line torque sensors (HBM, T20WN) of ±0.2% accuracy. Surface temperature of test gear was measured using the non-contact infrared temperature sensor (Raytek, MID10LT) with an accuracy of ±1 K. Torque and temperature data were measured and acquired using PC based data acquisition system (HBM, Spider 8) at a frequency of 50 Hz. To quantify the wear resistance of polymer gear, gear tooth thickness by base tangent length across three teeth was measured using 1 micron accuracy disc micrometer (Mitutoyo, 323-250) at three different marked positions at every 3 hour duration intervals. The gear weight loss was measured by weighing the test gear before and after the test using weighing balance of 0.1 mg accuracy (Sartorius, BSA224S-CW). Every test conditions were repeated for at-least three times and the average was considered. Initial surface roughness of the gear was measured with the aid of contact stylus type perthometer (Mitutoyo, Surftest SJ-401).

3. Results and Discussions

3.1 Surface morphology

In this work, test polymer gear was meshed with two type of gears (i) steel gear manufactured by hobbing followed by grinding and (ii) steel gear manufactured by WEDM. The gear surface of conventional machined gear, WEDM and injection moulded polypropylene gear are shown in Fig. 3(a)~(c).

Fig. 4(a)~(b) shows the tooth surface of a gear manufactured by

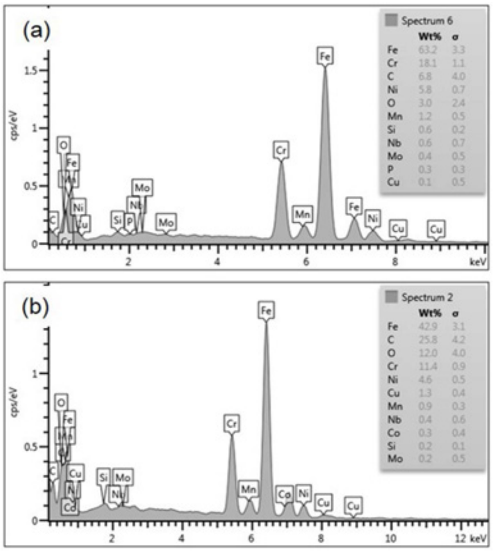

Fig. 5 EDX plot of (a) conventional machined surface and (b) WEDM surface

conventional machining. Conventional machined surface not exhibited any craters, pock marks and solidification layers of molten metal. In the WEDM, the spark produced the intense heat and hence metal is melted and removed. Some of the molten metal was flushed out by dielectric fluid and remaining metal solidified and formed lumps of debris. This recast layer consists of crater, pock marks and solidified spherical particles. The tooth surface of the gear manufactured by WEDM was observed under scanning electron microscope and shown in Fig. 4(c)~(d). Tooth surface exhibited rough and porous texture with crater due to the collapse of plasma. Bonney et al.[16] observed similar recast material containing droplets, craters and micro-cracks on the WEDM machined surface of ZrO_2-TiN composite. Murray and Clare[17] observed surface cracks on the AISI 310 stainless steel surface manufactured by electric discharge machining. Kumar et al.[18] reported similar kind of surface features on the titanium surface manufactured by WEDM process.

To confirm the presence of elements on the gear tooth surface, EDX was carried out. Fig. 5(a) shows the EDX plot of conventional machined gear. The major elements observed are Fe, Cr, C, Ni, and Mn, whereas Si, Nb, Mo, P, Cu are minor contents. A small percentage of oxide was also found in the surface. Fig. 5(b) shows the EDX plot of wire cut electric discharge machining surface. This surface exhibited enriched carbon and oxide content along with the other elements. The breakdown of hydrocarbon from the electrode and dielectric fluid during EDM process increased carbon and oxide contact on the surface. Sidhom et al.[19] also reported carbon enrichment on the AISI316L stainless steel surface during EDM process.

Fig. 6 shows the XRD plot of conventional machined and wire cut EDM surfaces. The XRD plot confirmed the presence of FCC γ-austenite phases in both the surfaces determined from the plane orientation. Nascimento et al.[20] also reported the presence of phases in the AISI 316L stainless steel surface. From the XRD analysis, crystalline size of the machined and WEDM surface was computed by using full width at half maximum using Scherrer's equation[21]

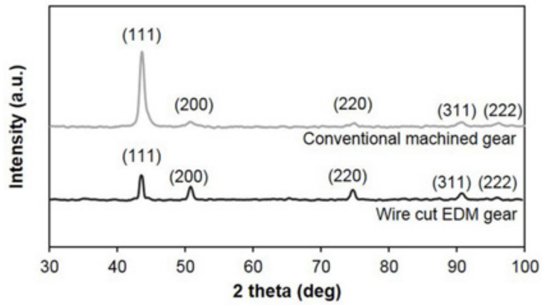

Fig. 6 XRD analysis of conventional machined and WEDM surface

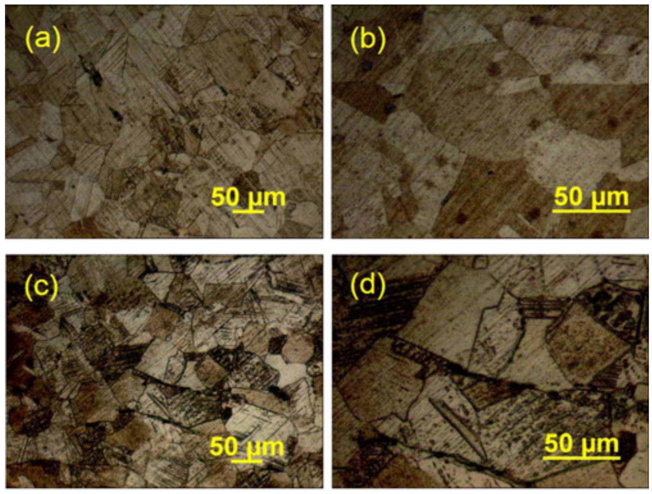

Fig. 7 Micro graph of gear tooth surface (a)~(b) machined surface (c)~(d) WEDM surface

$$a = \lambda / (\beta \cos\theta)$$

where,

a Crystalline size (Å)

λ wave length of X-Ray (1.5406 nm)

β Full-width at half maximum which is determined from XRD data (radian)

θ Diffracted angle (°)

The average crystal size of all the planes for the conventional machined surface is 8.5 nm, whereas for the WEDM surface it is 15.2 nm. This increased crystal size is due to dynamic crystallization of planes at high temperature induced by EDM process. Sidhom et al.[19] also observed this dynamic recrystallization behavior while evaluating white layer microstructure of AISI 316L stainless steel. Murray et al.[17,22] also discussed similar kind of XRD plot for austenitic steel after EDM, pulsed electron beam irradiation and compared with machined surface.

Gear tooth machined surface and WEDM surfaces were prepared and investigated for the grain size and shown if Fig. 7(a)~(d). Grain size of the WEDM surface was slightly smaller than that of machined surface. Extreme high temperature at short duration in the WEDM process contributes to reduce the grain size.

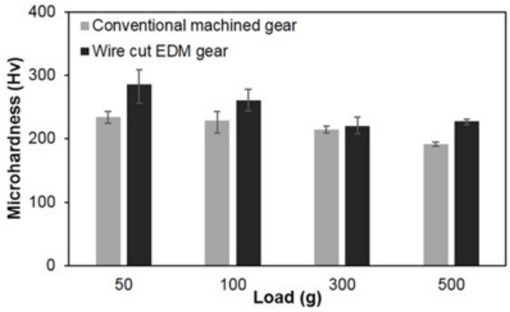

Fig. 8 Measured micro hardness of the considered counter gears

3.2 Micro hardness

Surface hardness of the mating gear would play vital role in the friction behavior with test polymer gear. Both the machined and WEDM surface was mirror polished then the hardness was measured with the aid of Vickers hardness tester (Buehler 1600) using a diamond pyramid indenter. After indentation, the diagonal of the indentation was measured and the hardness (HV) was computed based on the following equation,

$$HV = 1.854\ F/d^2$$

where,

F = Applied load (kgf)

d = Arithmetic mean of two diagonal (mm)

Fig. 8 shows the measured micro hardness of the conventional machined and WEDM surfaces. The carbon enrichment, increased crystal size and reduced grain size due to the WEDM contributes for the increased hardness. Gupta and Jain[2] also observed an increased micro hardness while manufacturing miniature spur gears through WEDM.

3.3 Surface morphology

Three dimensional surface profiler images of mating conventional machined and wire cut EDM gears are shown in Fig. 9. From the figure it is revealed that WEDM gear tooth surface exhibited more undulations when compared to that of conventional machining. The surface topography can be indexed by the bearing ratio. The bearing ratio curve of the mating metal steel gears is shown in Fig. 10. Conventional machined gear tooth surface exhibited superior load bearing capability at any considered surface depth.

Bergseth et al.[1] also reported similar kind of 3D surface profiler images and predicted the real area of contact and mean contact pressure exerted by the surface due to different manufacturing process hobbing grinding honing and green shaving. For the applied 2500 N normal load, the exerted mean contact pressures were 2800, 1500, 1200 and 1200 MPa for hobbing, grinding, honing and green shaving respectively. Thus surface with higher surface roughness generate more contact pressure. In the present case, the average surface roughness of the conventional machined and wire cut EDM gear was in the range of 0.41~0.48 and 4.74~5.26 μm respectively. Thus gear manufactured by WEDM would generate more contact pressure when paired with test polymer gear. Surface roughness (Ra) of the injection molded polypropylene gear was

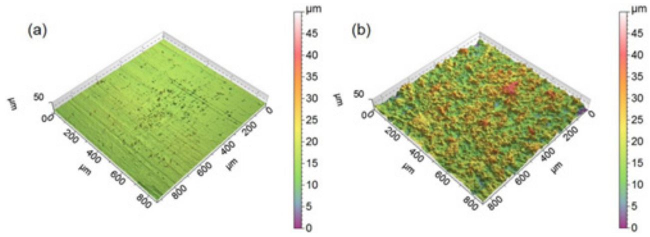

Fig. 9 Three dimensional profiler image of (a) conventional machined gear tooth surface and (b) gear tooth surface manufactured by WEDM

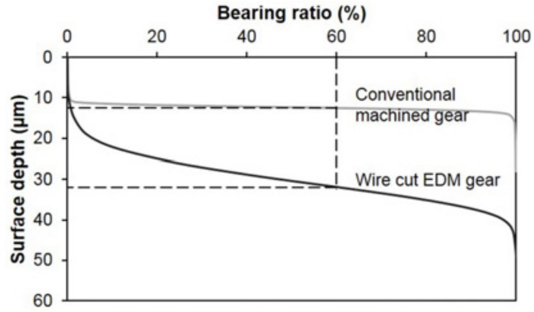

Fig. 10 Bearing ratio curve of mating steel gears

2~2.6 μm.

3.4 Polymer gear performance

The net surface of the polymer gear against conventional machined and wire cut EDM gear at 2, 2.5 and 3 Nm is shown in Fig. 11(a)~(c). Polymer gears exhibited a temperature rise of 10~15°C while tested against wire cut EDM gear when compared to conventional machined mating gear. The reason for this behavior is explained as follows.

Mating steel gear manufactured through WEDM exhibited higher surface roughness and hardness when compared to that of conventional machined gear. A polymer test gear mate with a steel gear with poor surface roughness and higher hardness, more amount of heat is generated due to increased friction. Hard surface of the WEDM gear ploughs the soft polymer gear (72 shore D hardness) and causes higher friction and surface temperature.

For all the gear tests, initially there was a gradual rise in temperature and then it reaches a steady state temperature due to the balance between heat generation and heat dissipation. The polymer gear tested against wire cut EDM gear at 3 Nm causes thermal induced fatigue failure confirmed by the sudden rise in surface temperature. However there was no such sudden rise in temperature at 2 and 2.5 Nm load. The nominal contact stress at the pitch region was calculated based on Buckingham's contact stress equation.[23] The contact stresses at the pitch point of the test gear were found to be 43.9, 49.2 and 53.8 MPa respectively for the applied torques 2, 2.5 and 3 Nm. With the increase in applied load, the contact stress and tooth deformation increases which significantly increases the net surface temperature of the test gears. Guha and Chowdhuri[24] reported that the effect of surface roughness on the surface temperature of a sapphire pin against carbon steel disc at 17 N and 2 m/s. The disc was machined by grinding,

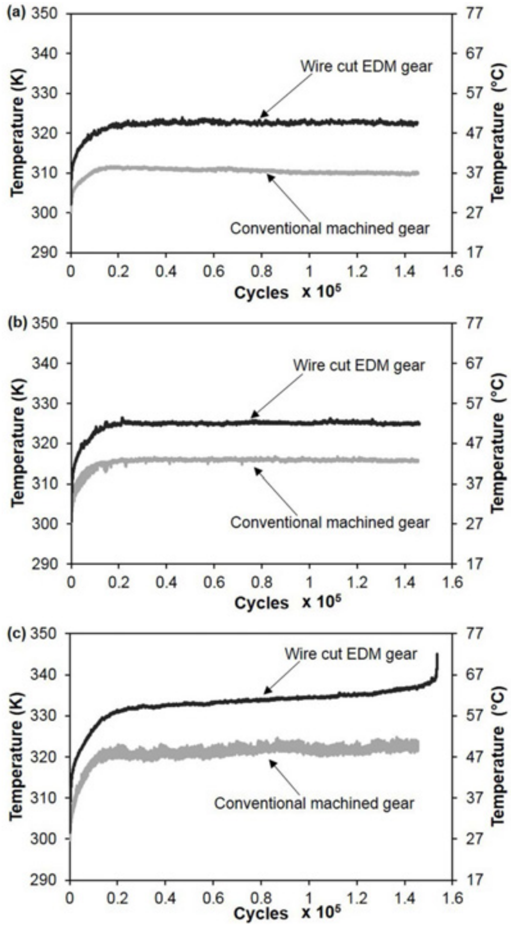

Fig. 11 Measured surface temperature of test gears when paired with conventional machined gear and WEDM gear at (a) 2 Nm, (b) 2.5 Nm and (c) 3 Nm

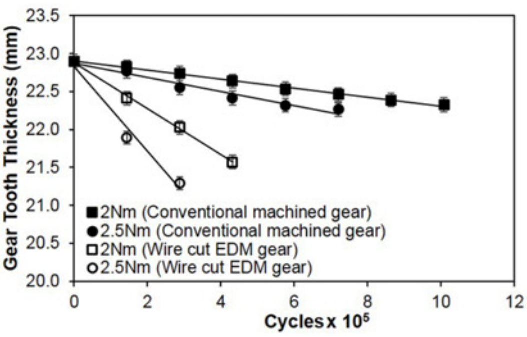

Fig. 12 Measured gear tooth thickness

polishing and shot-blasting to make a broad range of surface finish (0.05, 0.13, 0.23, 0.92, 1.47 and 3.01 μm). At 17 N and 2 m/s, the maximum surface temperature of 430°C was obtained for 3.01 μm roughness disc and 378°C surface temperature was obtained for 0.05 μm roughness disc.

The gear tooth thickness of the test gears was measured periodically (every 3 hours, 1.44×10^5 cycles) to understand the wear performance of test gears against conventional machined and wire cut EDM gear.

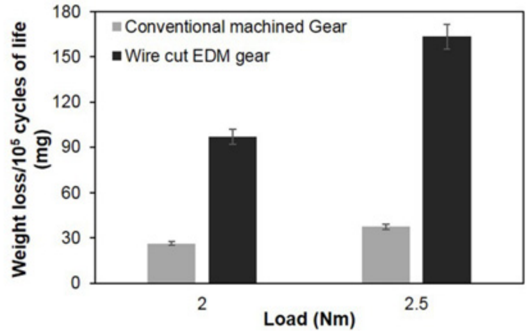

Fig. 13 Measured weight loss of polymer gear

The gear tooth thickness of test polymer gear measured across three teeth at 2 and 2.5 Nm and shown in Fig. 12.

At 2 and 2.5 Nm the test gears were run up to 10.05×10^5 and 7.2×10^5 cycles against conventional machined gear, whereas against wire cut EDM gear, test gears were run only up to 4.32×10^5 and 2.88×10^5 when subjected to 2 and 2.5 Nm load. Weight loss per 10^5 cycles of the test gear at 2 and 2.5 Nm load is shown in Fig. 13. The percentage weight loss per 0.1 million cycles of the polymer gears at 2 and 2.5 Nm against conventional machined gear is 0.3 to 0.4%, whereas against wire cut EDM gear it is 1 to 2%.

Akkurt[3] observed the effect of surface roughness of mating metal on the wear of acetal gears at 1000 rpm and 6.5 Nm. Wear loss of the acetal gear was maximum when the surface roughness of the mating metal gears was 0.56 μm and least at 0.09 μm roughness. Bonny et al.[25] also investigated the influence of EDM process on the tribological behavior of different surface finished tungsten carbide disc against tungsten carbide pins using pin-on-plate test rig for the test parameters of 15 N, 0.3 m/s and 10 Km sliding distance. By varying the process parameters, the rough surfaces were made in the range of 2.08-2.37 μm (Ra) and the fine surfaces were made in the range of 0.19-0.27 μm (Ra). The wear rate was high (2.7×10^{-7} mm^3/N/m) for rough surface compared to fine surface plate (4.6×10^{-9} mm^3/ N/m). And also the rough surface causes pronounced ploughing component due to abrasion when compared to finer surface.

The worn out surface of the test gears after finite number of cycles are shown in Figs. 14~16. For all the test conditions, test gears are subjected to wear failures expect the polymer gear against wire cut EDM gear at 3 Nm (thermal induced tooth deformation as shown in Fig. 16(b)). Test gear paired with WEDM gear (Figs. 14(b), 15(b)) exhibited excessive wear when compared to that of test gear paired with conventional machined gear (Figs. 14(a), 15(a)). Tested polypropylene gears (2~2.5 Nm) were observed under profile projector, almost uniform wear was observed at both addendum and dedendum region. In addition, the service life exhibited by the polymer gear when paired with WEDM gear is considerably less when compared to the polymer gear when paired with conventional machined gear. Wear marks and change in the sliding direction (ridge at pitch region) are distinctly visible in all the test conditions. Mao et al.[26] also reported the thermal induced bending failure of acetal-acetal gear pairs at the loads and speed of 10~16.10 Nm and 1000 rpm. Similarly Senthilvelan and Gnanamoorthy[27] observed thermal induced plastic deformation of Nylon 66 gear against identical

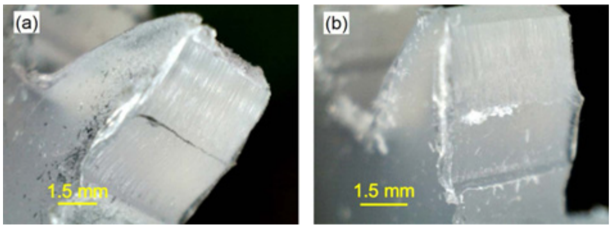

Fig. 14 Worn out of test gear at 2 Nm against (a) conventional machined gear (after 10.08×10^5 cycles) and (b) WEDM gear (after 4.32×10^5 cycles)

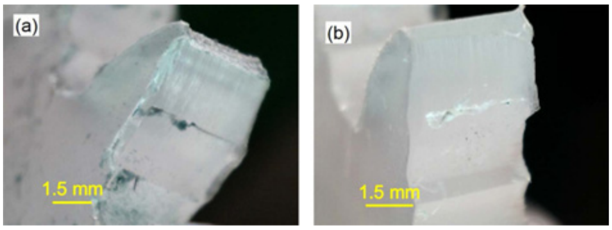

Fig. 15 Worn out of test gear at 2.5 Nm against (a) conventional machined gear (after 7.20×10^5 cycles) and (b) WEDM gear (after 2.88×10^5 cycles)

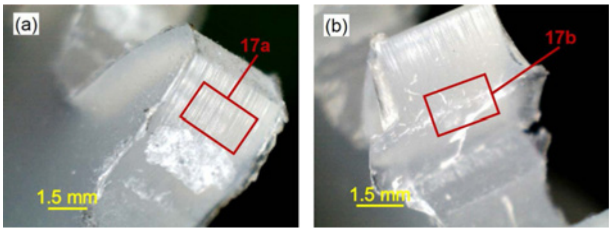

Fig. 16 Worn out of test gear at 3 Nm against (a) conventional machined gear (after 1.44×10^5 cycles) and (b) WEDM gear (after 1.54×10^5 cycles)

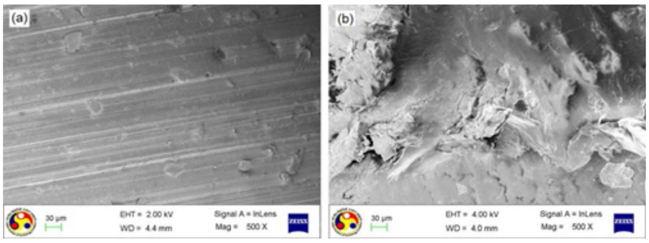

Fig. 17 Close up view of the test gear at 3 Nm against (a) conventional machined gear (after 1.44×10^5 cycles) and (b) WEDM gear (after 1.54×10^5 cycles)

steel gear at the load and speed of 3 Nm and 1000 rpm.

Worn out polypropylene gears tested at 3 Nm against the machined steel gear and WEDM were further observed under scanning electron microscope. Polymer gear tested against machined steel gear showed dominant abrasive wear (Fig 17(a)). Polymer gears tested against WEDM showed dominant plastic deformation (Fig. 17(b)).

4. Conclusions

Durability of injection molded polypropylene gear was evaluated when paired with two types of steel gears (a) manufactured by gear hobbing followed by grinding and (b) wire cut electric discharge machining process. Due to the difference in surface topology and hardness between these two mating gears, test polymer gears exhibited significantly different performance.

- Polymer gears paired with a WEDM gear generates more heat due to the poor surface topology and increased hardness.
- Measured gear tooth thickness at lower loads (2~2.5 Nm) and inspection at various stages of service confirmed the superior performance of polymer gears when paired with hobbed gear compared to that of the WEDM gear.
- At higher loads, polymer gears exhibited thermal fatigue failure when paired with WEDM and only excessive wear was observed without any tooth deformation when polymer gears are parried with the machined gear.

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