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INFLUENCE OF CARBON FIBER REINFORCEMENT OVER THE ACCURACY OF INJECTION MOLDED POLYMER GEAR

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Abstract: *Injection molded polymer based gears are not preferred for precision motion applications due its directional shrinkage behavior. This paper attempts to predict the material shrinkage of unreinforced and carbon fiber reinforced nylon gears and correlate with gear metrological parameters. Fiber alignment along the tooth profile restricts the shrinkage and induces anisotropic shrinkage, which significantly decrease the deviation of involute profile parameter from the design values. Fibers embedded in the molded skin surface increases the gear tooth profile form deviations. Non-alignment of fibers across the gear tooth section increases tooth thickness, tooth-to-tooth spacing and radial runout deviations from design values.*
Key words: *Injection molding; fiber orientation; anisotropy shrinkage; gear metrology*

1. INTRODUCTION

Gear manufacturing process considerably influences the accuracy/quality of gears produced. Variation in angular motion at the pitch line of a low accuracy gear causes localized load intensities in excess of design load and reduces the gear life. The transmission efficiency, noise and vibration level of power transmission gears are affected by the gear accuracy. Gear tooth deviation and elastic deformation of gear tooth under load causes non-uniform torque transmission from driver to the driven gear tooth (Frazer, 2000; Illinois Tool Works, 1990). The non-uniform transfer of torque causes dynamic loading and leads to increased sound and vibration in the system. In conventional metal gear manufacturing processes like gear hobbing and shaping, the gear blanks are mounted in-line with the machine tool axis and hence obtaining concentric features in metal gears is not difficult. This is not the case in the injection molding process, which is widely employed in manufacturing polymer-based gears (Kleiss & Kleiss, 1998). In the case of injection molded polymer gears, module correction and pressure angle correction methods are widely followed to provide shrinkage compensation. However, both the methods are based on the assumption that the shrinkage occurs toward the center of a molded gear, which is not always so in real cases (Lee et al., 1998). Standard thermoplastic mold shrinkage data are generated on a large number of test samples, which do not represent the flow, orientation, and heat transfer, which are generally observed in a typical molded gear. Geometrical accuracy of an injection-molded component is decided by many parameters such as material shrinkage characteristics, molding parameters, gating and cooling systems (Dominick et al., 2000). Complex geometry of gear causes different flow and shrinkage rates and affects the gear accuracy.

The effect of manufacturing errors, deformation and wear on transmission characteristics of polymer-based gears were reported at Nagarajan & Rayudu (1987). Luscher et al. (2000) investigated the geometry and transmission errors in injection molded polymer gears made with different gate configurations. The effect of gating scheme and packing pressure on the gear run-out, lead variation, and transmission error were also reported. Williams and Kleiss (1999) investigated the effect of internal lubricants on the accuracy of injection molded thermoplastic gears. Gear dimensions such as diametrical pitch, outside, root, pitch, and base circle diameters, and tooth thickness were considered by the researchers. The effect of injection pressure, cavity thickness, fiber concentration and gate location on orientation of fibers in the product design was reported (Zainudin et al., 2002).

Many research works have been reported on numerical simulation of short fiber reinforced polymer materials and their influence on some mechanical properties. However, the effect of fiber orientation on the accuracy of molded part is not reported so far. This paper describes the computer-aided simulation of unreinforced and carbon fiber reinforced Nylon 6/6 gear processing carried out to understand the gating and fiber orientation effect on part shrinkage. Detailed metrological inspection of the molded gears was carried out and results were correlated with simulation results of fiber orientation in the gear.

2. COMPUTER AIDED SIMULATION OF GEAR MOLDING

Computer aided engineering analysis of injection molding process helps to design the appropriate mold dimensions so that the gears can be molded within the required tolerance limits. Knowledge of melt front progression, orientation effects, differential shrinkage and the part warpage are required to develop high quality gears. Injection molding simulation of the gear molding process was carried out using the commercial mold flow software, Mold Flow Plastics Insight®.

A three-dimensional gear model is generated using the commercial modeling software, Mechanical Desktop® and imported into Mold Flow Plastics Insight®. The model is meshed using the fusion option using triangular elements. The meshed part statistics indicates a match ratio of 90 % and average aspect ratio of 2.677, which are well within the limits to carry out the fill and shrinkage analysis (Users manual, 2000). Unreinforced Nylon 6/6 and 20 % carbon fiber reinforced Nylon 6/6 were considered for the simulation of gear manufacturing.

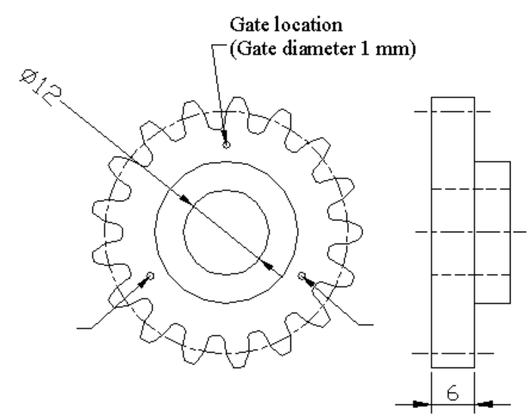

Fig. 1 Test gear details and gate locations

Nomenclature	
Pressure angle	20^0
Number of teeth	17
Module (mm)	2
Face width (mm)	6
Hub diameter (mm)	18
Bore diameter (mm)	12

Table 1 Test gear nomenclature

3. TEST GEARS AND MOLDING CONDITIONS

Unreinforced Nylon 6/6 and 20 % carbon fiber reinforced Nylon 6/6 granules were used for molding the spur gears. The details of molded test gears are shown in Figure 1 and Table 1. The granules were preheated for 4 h at 353 K to remove the moisture content before injection molding. Three symmetrical pin pointed gates, which causes symmetric melt flow (Beaumont et al., 2002) is considered for injection molding of the unreinforced and carbon fiber reinforced gears. Test gears were molded in the laboratory using an injection molding machine (Macfield).

4. METROLOGICAL INSPECTION OF MOLDED GEARS

Unreinforced and reinforced molded gears were inspected using a fully automatic computer numerical controlled gear-measuring center (Klingelnberg P 40). The involute profile, tooth-to-tooth spacing, and radial runout deviation were measured and plotted according to DIN 3962, 1994. The profile measurements were done in both the left and right flanks of three marked teeth, which are equally spaced. For tooth-to-tooth spacing measurement, both left and right flanks of all 17 teeth were considered. The total involute profile deviation is measured along the actual involute curve of the gear tooth between the base circle and tip circle diameter. A cumulative average line is drawn over the actual measured involute profile, and deviation from the cumulative average line is the involute profile form deviation. Surface condition of the involute-profile is known by the involute-profile form deviation. The algebraic difference between the actual pitch and corresponding theoretical pitch in the transverse plane defined on a circle concentric with the gear axis is pitch deviation / tooth-to-tooth spacing deviation.

5. FIBER ORIENTATIONS

In general, shrinkage of a polymeric material is determined by measuring the shrinkage of a rectangular bar of specified dimension as per ASTM D-955, 2004. For the test gear materials, mold shrinkage for a particular part thickness is given by the material supplier (Product data sheet, 2003). These shrinkage values are corresponding to the dimensions parallel and perpendicular to the direction of the melt flow in a part. In real conditions mold shrinkage vary with part thickness, mold layout, processing conditions and mold temperature (Menges et al., 1985). During injection molding of fiber-reinforced polymers, the incorporation of fibers causes a significant effect on linear shrinkage. The fiber orientation and distribution in an injection-molded component is a function of component geometry, molding conditions (gating, temperature, pressure and holding time), matrix material, polymer melt viscosity, and fiber type (aspect ratio, density and volume fraction) (Weale et al., 1998). Complicated geometry of a gear influences the fiber orientation and distribution. The shear forces within the melt also affect the fiber alignment. During injection molding, molded gear part form core and shell structures. In the shell region (mold wall / skin), due to the strong shear force, fibers tend to align along the melt flow direction. However, in the core region, no shear force exists and hence fibers are aligned transverse to the flow direction (Hee Han & Taek Im, 2002).

6. RESULTS AND DISCUSSION

6. 1. Simulations and observation of fiber orientation

The average orientation of reinforced fibers in the molded gear using mold flow simulation for the selected gear geometry and injection point is shown in Figure 2. The anisotropy parameter varies between 0 and 1. One indicates the perfect alignment of the fibers parallel to the reference direction and zero indicates the perfect perpendicular alignment to the reference direction (Han Seong, 2004). In the tooth region, most of the fibers are oriented along the gear tooth profile. A qualitative examination is carried out using optical microscope to find out the fiber orientation in the molded gear. Observation of polished surface between the teeth as well as tooth addendum also confirms the fiber orientation along the part boundary. Detailed results were discussed elsewhere (Senthilvelan and Gnanamoorthy, 2006a).

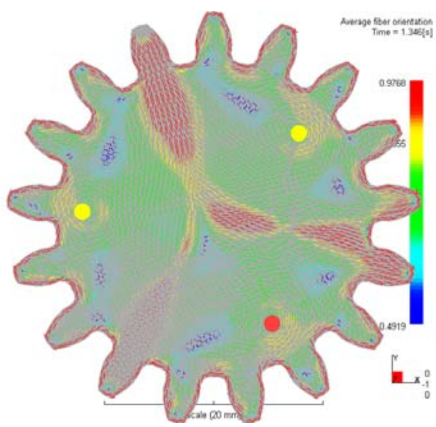

Fig. 2 Predicted average fiber orientation in glass fiber reinforced Nylon 6/6 gear.

6.2 Gear tooth profile deviations

An involute profile plot of a gear tooth indicates the deviation of total involute profile ($F\alpha$), and involute profile form ($ff\alpha$) from the design values. Figures 3a and b show the involute profile deviations in unreinforced and carbon fiber reinforced gears respectively.

If there is no deviation from the designed involute profile, then the traces would be straight vertical lines. The involute profile deviations in left and right flank surfaces of three teeth (tooth no. 1, 6 and 12) are shown in a single plot. No appreciable profile deviation was observed among three teeth as well as between the left and right flank surfaces (Figures 3a and 3b) and hence the average value were considered taken for further conclusions. The involute profile was measured from the tip circle to base circle diameter. In the profile plot, the position of tip and root of a gear tooth as well as chosen horizontal and vertical scales were shown.

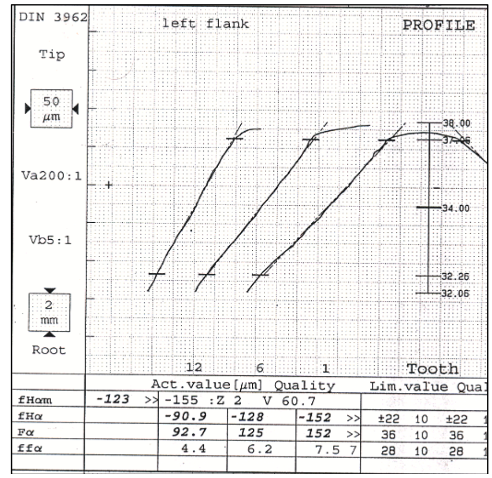

Fig. 3a Involute profile deviations in unreinforced Nylon 6/6 gear -left flank

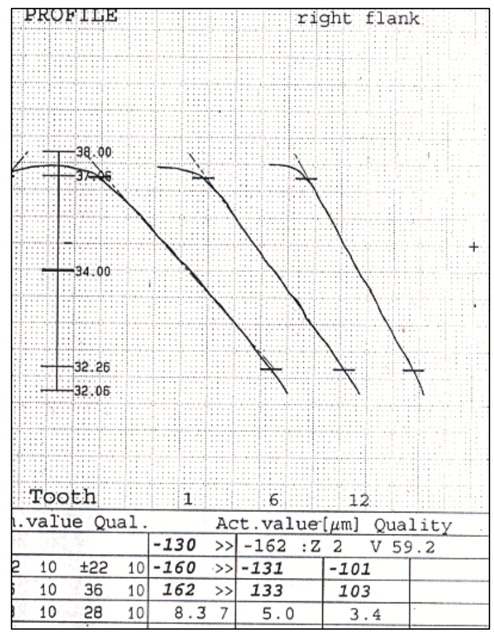

Fig. 3b Involute profile deviations in reinforced Nylon 6/6 gear-right flank

In injection molded reinforced gears, fibers are oriented along the gear tooth involute profile since the melt flow direction is along the gear tooth profile (Figure 2). The maximum involute profile deviations (Fα) in the unreinforced and carbon fiber reinforced Nylon 6/6 gears are found to be 127.9 μm and 10.03 μm respectively. Carbon fiber reinforced Nylon 6/6 gears exhibited a less involute profile deviation compared with unreinforced Nylon 6/6 gears. Incorporation of fibers along the gear tooth profile reduces the shrinkage in the gear tooth involute profile and helps to achieve a near perfect involute profile. For conjugate action and for uniform motion and power transmission, very small deviation from involute profile is preferred.

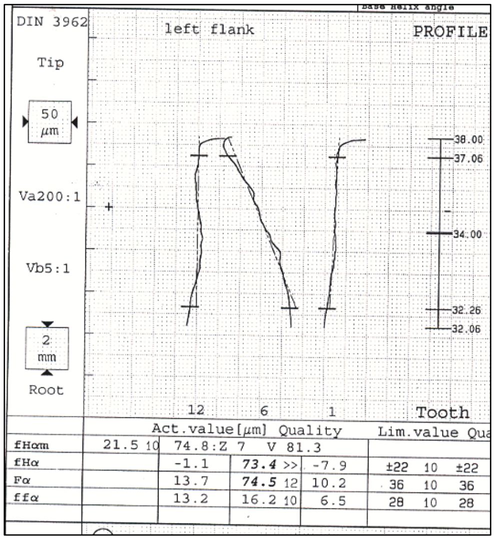

Fig. 3c Involute profile deviations in carbon fiber reinforced Nylon 6/6 gear -left flank

The involute profile form deviation (Ffα) is less in unreinforced gears due to the homogenous nature of unreinforced Nylon 6/6 melt at the skin (Figure 3a). Whereas in carbon fiber reinforced Nylon 6/6 gears, hard carbon fibers embedded in the skin of gears affect the smoothness of gear profile and increase the involute profile form deviation (Figure 3c). The maximum involute profile form deviation in unreinforced and carbon fiber reinforced Nylon 6/6 gears are found to be 5.7 µm and 11.1 µm respectively. If there is no form deviation, then measured curve should exactly merge with the mean (shown as chain line) irrespective of the deviation from the vertical line. Surface roughness of the molded gear is influenced by the form deviation parameters. For low torque and high precision applications, form deviation significantly contributes to the gear performance.

6. 3 Gear tooth pitch deviation

Injection molded polymer based gears show non-uniform shrinkage due to the difference in the location of individual gear tooth from the injection point. Difference in distance from injection location to various gear teeth causes variation in viscous condition, cooling rate, and packing pressure in the mold. Hence the thickness of all the teeth and spacing between adjacent teeth of molded gear are not uniform. Unreinforced and carbon fiber reinforced molded gears were inspected for tooth-to-tooth spacing / pitch deviation (*fp*). Figures 4a and b show the tooth-to-tooth spacing deviation in left and right flank of test gears. This plot indicates the deviation of spacing between adjacent teeth for all the 17 teeth of test gears. Unreinforced gear exhibits a marginal deviation of tooth-to-tooth spacing due to the variation of distance of individual gear tooth from the gate locations.

In reinforced gears, the presence of fibers alters the material homogeneity across the tooth region and induces more tooth-to-tooth spacing deviation than unreinforced gear. Deviations in tooth spacing and tooth thickness cause varying tooth backlash which results in non-uniform engagement and disengagement during running. For gears running at high speeds, minimizing the pitch error reduces the noise and vibration levels in the transmission system. The effect of gear quality on the sound generated has been discussed in detail elsewhere (Senthilvelan & Gnanamoorthy, 2006b).

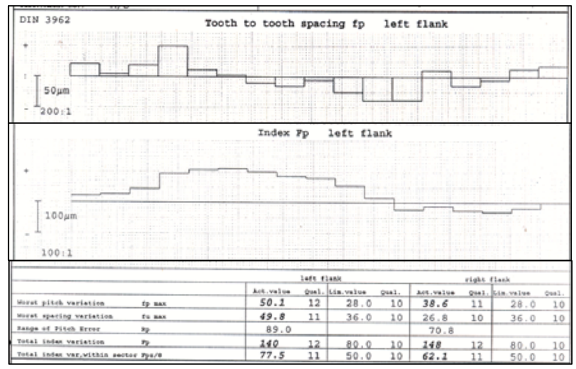

Fig. 4a Tooth-to-tooth spacing error in unreinforced Nylon 6/6 gear

Unreinforced and carbon fiber reinforced gears were inspected for pitch line / radial run out (Fr) and tooth thickness variation (Rs). Figures 5a and b show the radial runout of all the 17 teeth present in unreinforced and reinforced gears respectively. Due to the variation in distance from gate position both unreinforced and carbon fiber gears exhibits almost same runout deviations. The maximum radial runout of unreinforced and carbon fiber reinforced nylon gears are found to be 208 µm to 194 µm respectively.Whereas the presence of carbon fibers alters the material homogeneity across the tooth region of gear mold and the maximum tooth thickness variation increases from 107 µm to 150 µm.

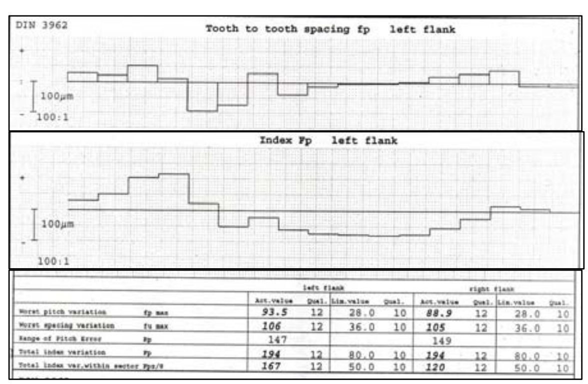

Fig. 4b Tooth-to-tooth spacing error in carbon fiber reinforced Nylon 6/6 gear

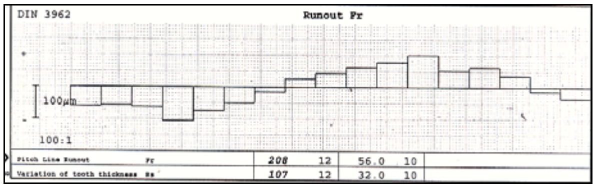

Fig. 5a Radial runout error in unreinforced Nylon 6/6 gear

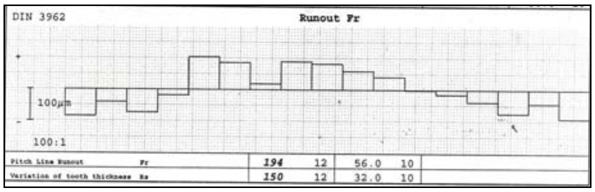

Fig. 5b Radial runout error in carbon fiber reinforced Nylon 6/6 gear

7. CONCLUSIONS

Detail metrological inspections were carried out on the injection molded unreinforced and carbon fiber reinforced Nylon 6/6 gears. The gear accuracy was correlated with the actual fiber orientation and simulated mold flow results and the following conclusions were drawn.

Alignment of carbon reinforced fibers along the gear tooth involute profile causes restricted shrinkage and hence a less total profile deviation was observed in reinforced gears compared with unreinforced gears.

Presence of carbon reinforced fibers in the molded surface of gear deteriorates the surface smoothness and the hence involute profile form deviations of reinforced gears are more than unreinforced gears. As each gear tooth is at different distance from injection point, radial run out deviation increases for both unreinforced and reinforced gears. Whereas in carbon fiber reinforced gears, presence of fibers across the tooth section affects the material homogeneity and hence induces more tooth thickness variation than unreinforced gears.

8. ACKNOWLEDGEMENTS

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