



# Prediction of injection molding parameters for symmetric spur gear

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## Abstract

Polymer gears pose major advantages, like noiseless operation, resistive against corrosion, low weight, ability to damp vibrations, ease of manufacturability, and ability to operate without lubrication like in printers, household appliances, etc. In order to enhance mechanical properties of gear materials, various reinforcing materials are added such as glass and carbon fibers. The orientation of these fibers and distribution are critical parameters at the microstructural level for polymer reinforced with short fibers, which defines the strength and life of gears. The geometric accuracy and precision of molded gears are improved by the injection molding technique. The fiber orientation prediction is a new and novel aspect for high performance and life, as these injection-molded gears have complex patterns of fiber orientation. This also affects material properties such as elastic modulus, strength, and gear geometrical dimensional properties shrinkage and warpage. In this present work, an attempt is made to develop 3D symmetric spur gear tooth geometry using Autodesk Fusion 360. The injection molding parameters such as fiber orientation tensor, volumetric shrinkage at ejection, weld lines, deflection, and confidence in filling are studied for modeled gear having symmetric teeth profile for unreinforced and 20%, 30%, 40%, 50%, and 60% glass fiber-reinforced nylon 6/6 (PA66) by using Autodesk Moldflow Adviser 2017. The result obtained from mold simulation tool indicates that fiber orientation tensor for varying glass fiber contents was close to unity. The volumetric shrinkage considerably reduced from unreinforced PA66 to glass-reinforced PA66.

**Keywords** Spur gear · Injection molding · Mold flow · Fiber orientation · Volumetric shrinkage

## Introduction

Composites can be regarded as a combination of two or more materials to overcome a weakness in one material by strength

### Highlights

- Development of 3D symmetric spur gear physical model
- Glass fiber reinforcement study from 20 to 60% in steps of 10
- To predict the orientation and alignment of fiber using Mold flow adviser 2017
- Identification of weld lines, shrinkage, and warpage in a simulation model

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along with reducing the weight of the material. This type of combination makes the composite materials to exhibit properties distinctly different from those of the individual materials used to make the composite. The major advantages of composites include lower material cost, low cycle time for manufacturing, and possibility of recycling after intended span of usage. As the composites gain prominence, the reinforcement which goes into the substrate is the focus of researchers. The reinforcement material will play a pivotal role in defining the overall strength of the structure. In this regard, fiber-related properties such as fiber material, orientation, and aspect ratio, and thermal, chemical, mechanical, and characteristic properties are playing a vital role. Among these many parameters, fiber orientation for polymer-based composite has come to the forefront in recent times. Moldflow software (Moldflow Corporation, Framingham, MA) is used for distributing the fiber orientation for printer nozzle with various internal geometries for arriving at the optimal design. The work demonstrates convergent nozzle geometry results in better fiber alignment in comparison to divergent design nozzle [1]. The nozzle geometry extrusion work continued with Heller et al., by including fiber orientation for short section polymer composite. COMSOL (Comsol Inc., Burlington, MA) software was considered for solving the case

of fiber orientation [2]. Recently, Heller et al. demonstrated the influence of polymer composite bead for a 2D planar flow model [3]. Thermal structural properties of the same 2D planar for fiber orientation used the homogenized method [4] where elastic constants and coefficient of thermal expansion were observed. In continuation to the work, polymer rheological properties were extracted for the same component [5]. Some of the works with fiber orientation have been successfully achieved at geometrically weak sections such as notches, fillets, holes, and weldment [6, 7]. Load bearing capacity of a component is decided based on the component's geometrical structure with its critical junctions; this has made researchers study the effect of fiber orientation at notches, fillets, and many more critical regions [8–12]. The effect of anisotropy of notches was studied with novel methodology under a local fiber orientation. However, the work did focus on how the notch radius and fiber orientation will depend on the strength of the fatigue-based notch model [13].

The fiber orientation heavily relies on molten metal flow while manufacturing along with rheological characteristics such as viscosity and visco-elastic properties, and processing variables such as injection temperature and pressure with geometrical shape and size [14]. These are currently the thrust areas in which advanced simulation packages such as Moldflow, Materials Studio, J-OCTA, ANSYS, and many more software are used by researchers striving for better correlations. Fiber orientation has a major effect on the mechanical properties; it directly depends on the fiber alignment, vertical to the substrate or horizontal to the substrate (perpendicular to the substrate or parallel to the matrix) [15]. The values which have a slight reduction in their properties with perpendicular case as the parallel condition enhanced the load bearing capabilities [16]. Many authors have said that fibers orientated in the direction of loading drastically improved the magnitude of the material response (increase in Young's modulus or decrease in creep resistance); this has led to decrease in time dependency of a composite [17–20]. The aim of the current work is to design and develop a experimental and simulation study of a symmetric spur gear using Moldflow Adviser, and identify through the root cause analysis for fiber orientation by exploring alternative ways and arriving at an optimal solution, to finally compare the results with an experimental model.

## Methods

The current work is initiated with the development of a computer-aided design model using Autodesk Fusion 360 software version 2017 as in Fig. 1. A symmetric spur gear tooth geometry for the same pressure angles on the drive side and coast side is generated with the support of Autodesk Fusion 360. For this work, glass fiber is considered the reinforcing



Fig. 1 3-D gear model

material and substrate/matrix as nylon 6/6. Parameters considered while developing the spur gear are highlighted in Table 1.

Furthermore, the work focuses on the embedding glass fibers into the holding matrix from 20 to 60% in steps of 10%. The solid model is imported in Autodesk Moldflow Adviser 2017 R software for composite analysis. The effects of fiber orientation, concentration of fibers, type of matrix, and temperature were the study areas.

## Material and methods

From the material library of Autodesk Moldflow Adviser 2017 R, equivalent materials are Zytel 101 NC010, Akulon, R624-GS4U BK2989, Zytel 70G30HSL BK039B, MRGF1518 BK, Akulon S223-HG0 Natl, and PDX-R 98372 EES Natural. Furthermore, basic mechanical properties are showcased in Table 2.

## Estimation of module and number of tooth to avoid interference and undercutting

The module of a gear is one of the major and determining parameters of the gear. To generate gear profile, it is required to estimate the minimum value of module to transmit a power of 15 kW at a rated speed of 1000 rpm. The minimum number of teeth on pinion to mate with a rack without interference and undercutting = 18, module = 2 mm [21]. In Table 3, gear tooth parameters for different pressure angles on coast and drive sides are presented.

Table 1 Geometry and nomenclature of gear

Geometry and nomenclature	Value
Pressure angle (°)	20
Number of teeth	18
Module (mm)	2
Face width (mm)	6
Pitch diameter (mm)	36
Outside diameter (mm)	40
Bore diameter (mm)	16

**Table 2** Mechanical properties and injection parameters of materials

Sl. no.	Materials	Modulus of elasticity (MPa)	Shear modulus (MPa)	Poisson's ratio	Melt density (g/m <sup>3</sup> )	Melt temperature (°C)	Machine injection pressure (MPa)
01	Unreinforced Nylon 6/6	1400	518.5	0.35	0.97	290	125
02	20% glass fiber-reinforced Nylon 6/6	$E_1 = 6530$ $E_2 = 5460$	1730	$\nu_{12} = 0.38$ $\nu_{23} = 0.55$	1.32	270	125
03	30% glass fiber-reinforced Nylon 6/6	$E_1 = 8339.55$ $E_2 = 5047.23$	2135.28	$\nu_{12} = 0.42$ $\nu_{23} = 0.46$	1.11	294	125
04	40% glass fiber-reinforced Nylon 6/6	$E_1 = 11,393.1$ $E_2 = 6401.72$	2818.69	$\nu_{12} = 0.41$ $\nu_{23} = 0.48$	1.29	290	125
05	50% glass fiber-reinforced Nylon 6/6	$E_1 = 13,800$ $E_2 = 8440$	2740	$\nu_{12} = 0.37$ $\nu_{23} = 0.42$	1.40	290	125
06	60% glass fiber-reinforced Nylon 6/6	$E_1 = 15,300$ $E_2 = 11,900$	3660	$\nu_{12} = 0.33$ $\nu_{23} = 0.47$	1.55	290	125

Spur gears with symmetric profiles are generated using Eq. (1). The Cartesian coordinate ( $x_i, y_i$ ) of gear profile at any radius  $r_i$  is given by:

$$x_i = r_i \cdot \cos\theta_i, y_i = r_i \cdot \sin\theta_i \tag{1}$$

Where,

$$\theta_i = \frac{\pi}{2.z} + \tan\alpha - \alpha - \left( \tan\left( \cos^{-1}\left( \frac{r_p}{r_i} \cdot \cos\alpha \right) \right) - \left( \cos^{-1}\left( \frac{r_p}{r_i} \cdot \cos\alpha \right) \right) \right) \tag{2}$$

$r_p$  Standard pitch radius

$r_i$  At any radius

The Cartesian coordinate ( $x_i, y_i$ ) values of gear profile at any radius  $r_i$  are obtained from Eq. (1) using Microsoft Excel. The Cartesian coordinate ( $x_i, y_i$ ) values are imported in Auto CAD 2018 and the gear profile is created. The gear profile is imported in Autodesk Fusion 360 for 3D modeling of gear. Furthermore, the 3D gear model can be imported to a finite element analysis tool.

Percentages of glass fiber procurement along with trade name and coding were depicted in Table 4.

### Simulation study

As Industry Internet of Things (IIOT) gains importance in the twenty-first century, one among the nine modules which will

**Table 3** Gear tooth parameters for different pressure angles on coast and drive sides

Sl. no.	Description	Values
01	Number of teeth on pinion	18
02	Module	2 mm
03	Pressure angle on coast side	20°
04	Pressure angle on drive side	20°
05	Profile shift factor	0

rule the world is simulation. The study of simulation has become quite obvious in most of the applications. In case of gear composite analysis, the following conditions were considered.

### Molding conditions

Three symmetrical pin-point gates are used; melt temperature and machine injection pressure selected to achieve successful filling of mold are as shown in Table 2. These symmetrical pin-point gates help gears achieve uniform filling of mold and fiber orientation.

### Fiber orientation

Due to the use of three pin-point gates and location of these gates, the molten materials meet at three different regions. Moreover, these regions form weldment lines. Figure 2 shows regions of formation of weldment lines and Fig. 3 shows formation of weldment lines. The formation of weldment lines is also seen for gears simulated for varying percentages of glass fiber reinforcing nylon 6/6.

In the tooth region, most of the fibers are oriented along the profile of the gear tooth as shown in Fig. 4.

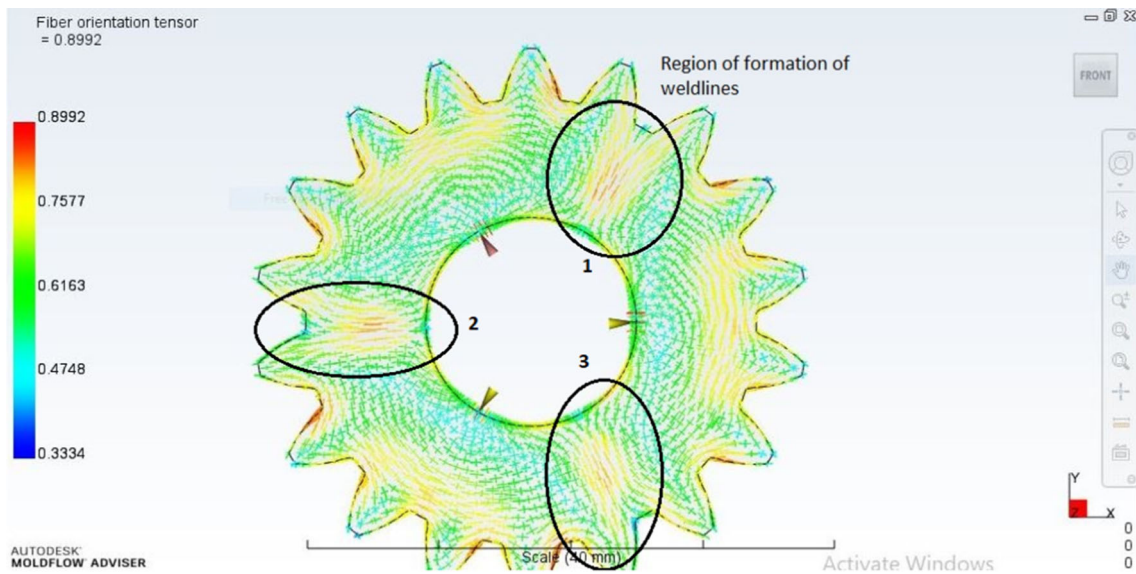
Since glass fibers are oriented in the radial direction, for 20% glass fiber-reinforced nylon 6/6, less shrinkage of 5.33% is observed at the tip circle of the gear. However, in some regions like hub shown in Fig. 5, more shrinkage of 11.40% is observed because of non-alignment in fibers. This observation almost remains the same for gears simulated by varying percentages of glass fiber reinforcing nylon 6/6.

### Effect of shrinkage on face width of gear

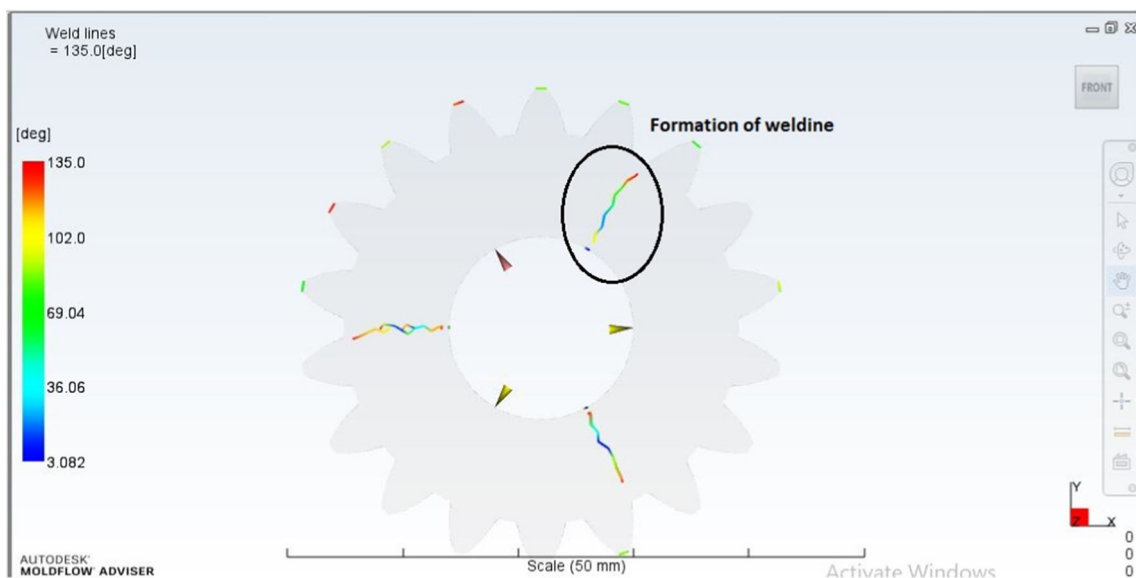
Since nylon 6/6 is semi-crystalline in nature, this causes higher shrinkage than amorphous materials. The volumetric shrinkage is non-uniform across the section of gear; the deviation in face width dimensions of gear for varying percentages of glass reinforcement is compared with that of unreinforced

**Table 4** Shows trade name and % fiber content for unreinforced and reinforced Nylon 6/6

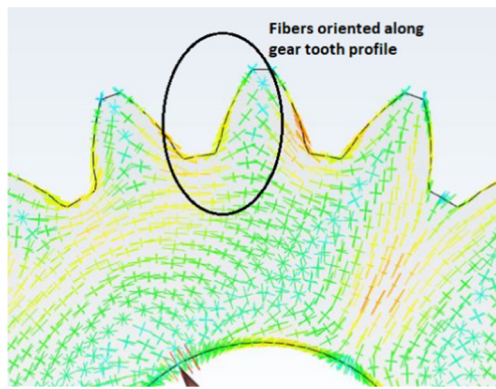
Sl. no.	Material	Trade name	% fiber content
01	Unreinforced Nylon 6/6	Zytel 101 NC010	Unfilled
02	20% glass fiber–reinforced Nylon 6/6 (PA66 20%GF)	Akulon R624-GS4U BK2989	20% glass fiber
03	30% glass fiber–reinforced Nylon 6/6 (PA66 30%GF)	Zytel 70G30HSL BK039B	30% glass fiber
04	40% glass fiber–reinforced Nylon 6/6 (PA66 40%GF)	MRGF1518 BK	40% glass fiber
05	50% glass fiber–reinforced Nylon 6/6 (PA66 50%GF)	Akulon S223-HG0 Natl	50% glass fiber
06	60% glass fiber–reinforced Nylon 6/6 (PA66 60%GF)	PDX-R 98372 EES Natural	60% glass fiber



**Fig. 2** Regions of formation of weldment lines



**Fig. 3** Formation of weldment lines



**Fig. 4** Fibers oriented along gear tooth profile

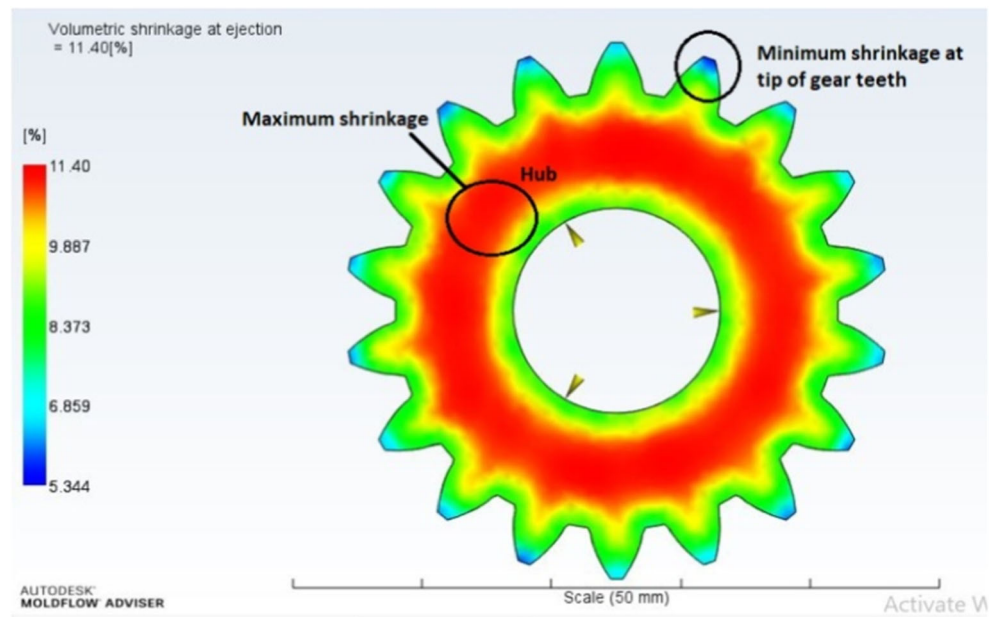
nylon. Table 5 shows face width deviation of gear for different materials.

## Results and discussion

### Test gears and molding conditions

The details about the gear dimensions are shown in Table 1. Three symmetrical pin-point gates, which causes symmetric melt flow as shown in Fig. 6, are considered for injection molding of the unreinforced and 20%, 30%, 40%, 50%, and 60% glass fiber-reinforced gears. Fill, pack, and wrap analysis is conducted on the modeled gear having symmetric and asymmetric teeth profiles for unreinforced and 20%, 30%, 40%, 50%, and 60% glass fiber-reinforced nylon 6/6 (PA66). The results obtained from the analysis such as fill time, weld lines, fiber orientation tensor, injection pressure, volumetric shrinkage at ejection, deflection, and warpage for

**Fig. 5** Volumetric shrinkage for 20% glass fiber-reinforced Nylon 6/6



unreinforced and 20%, 30%, 40%, 50%, and 60% glass fiber-reinforced nylon 6/6 (PA66) are shown in Table 6.

### Fiber orientation

The mechanical and thermal properties of fiber-reinforced composites depend strongly on the orientation patterns of the fibers. So, the study on the fiber orientation plays a very important role in the study. The average orientation of reinforced fibers in the molded gear for the selected gear geometry and injection point is shown in Fig. 7 (a–e).

The anisotropy parameter varies between 0 and 1: 1 indicates the perfect alignment of the fibers parallel to the reference direction, and 0 indicates the perfect perpendicular alignment to the reference direction [22]. At the injection point, due to the pin-point gate, fibers are spreading outward from the injection point. The use of three pin-point gates and location of these gates, resulted in the molten material to meet at three different regions. The average fiber orientation tensor for different gear profiles and varying percentages of glass fiber ranges from 0.6 to 0.7. It is also observed that fiber orientation near the tooth region is uniform throughout the gear. The fibers near the weld lines are oriented along the flow direction.

### Volumetric shrinkage

In general, the semi-crystalline nature of nylon 6/6 material causes higher shrinkage than an amorphous material. The molecular structure of a semi-crystalline material allows the polymer chains to align in an ordered manner as the polymer molecules cool. This alignment imparts directional shrinkage [22]. It is observed from Fig. 8 (a–f) for unreinforced and

**Table 5** Face width deviation of gear for different materials

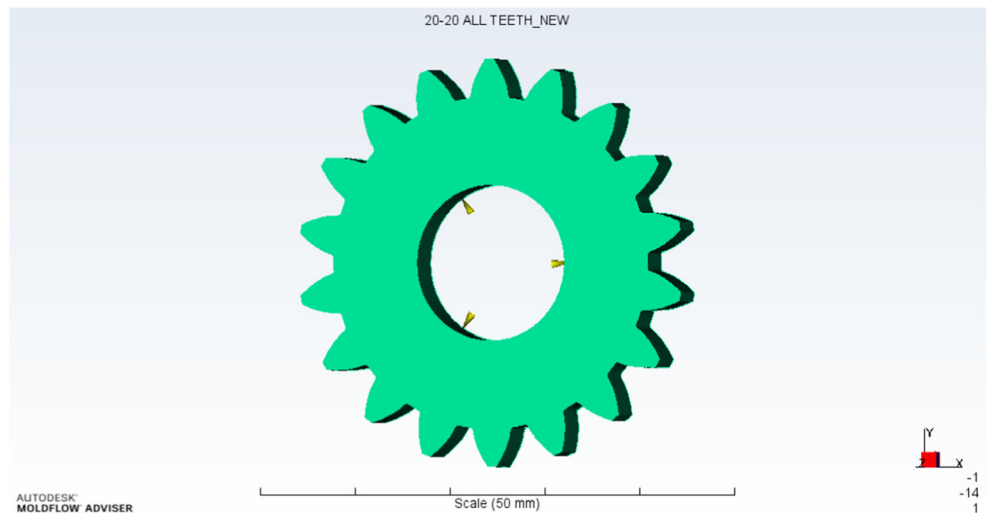
Material	Unreinforced Nylon 6/6	20% glass fiber–reinforced Nylon 6/6	30% glass fiber–reinforced Nylon 6/6	40% glass fiber–reinforced Nylon 6/6	50% glass fiber–reinforced Nylon 6/6	60% glass fiber–reinforced Nylon 6/6
Face width deviation in %	12.33	3.893	5.698	3.36	4.045	3.933

reinforced gears that shrinkage across the section is not uniform. The maximum percentages of volumetric shrinkage for unreinforced and glass fiber–reinforced gears are 12.36 and 10.04%, respectively. Inclusion of increasing glass fiber content in PA66 resin reduces the volumetric shrinkage of the gears [23]. It is also seen that for unreinforced and reinforced gears, shrinkage at the gear tooth tip is less. However, more shrinkage is observed in the case of hub and bore section as shown in Fig. 8a. The same type of variation is seen for different glass fiber contents. The simulation study will hold good if the percentage of error is varying in range of less than

5% [24, 25] for structural and less than 20% for composite matrix [26].

The study revealed an effect of volumetric shrinkage of unreinforced PA66 and glass-reinforced PA66 molded gear. Major dimensions of gear such as tip circle diameter, face width, and bore diameter were measured using a gear tooth flange micrometer with 1-mm accuracy. For both reinforced and unreinforced test gears, five gears, and each gear parameter, three measurements extracted at different positions and the mean value are considered for analysis.

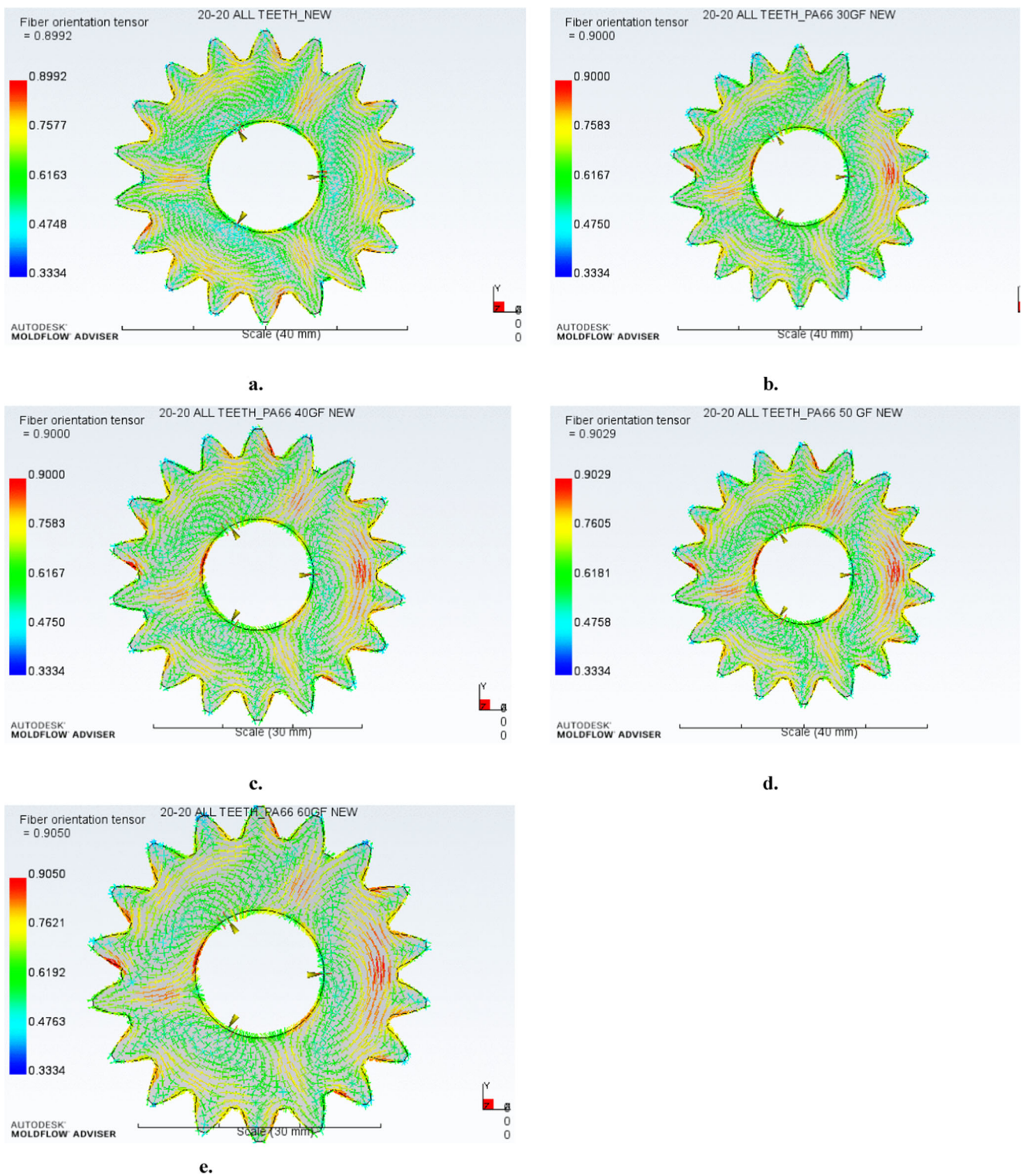
**Fig. 6** Three symmetrical pin-point gates for model gear



**Table 6** Show the effect of molding parameters on 20–20° gear profile for materials

Gear profile	Molding parameters	Materials					
		PA66 unfilled	PA66 20%GF	PA66 30%GF	PA66 40%GF	PA66 50%GF	PA66 60%GF
20–20	Filling time (s)	0.1009	1.011	2.052	2.56	3.063	3.11
	Confidence in filling (%)	H	H	H	H	H	H
	Weld line	P	P	P	P	P	P
	Fiber orientation tensor	NA	0.8992	0.9	0.9	0.9029	0.9050
	Volumetric shrinkage at ejection (%)	12.36	11.40	14.69	10.75	10.17	10.04
	Deflection (mm)	0.7399	0.2336	0.3419	0.2020	0.2427	0.2360
	Warping indicator	L	L	L	L	L	L

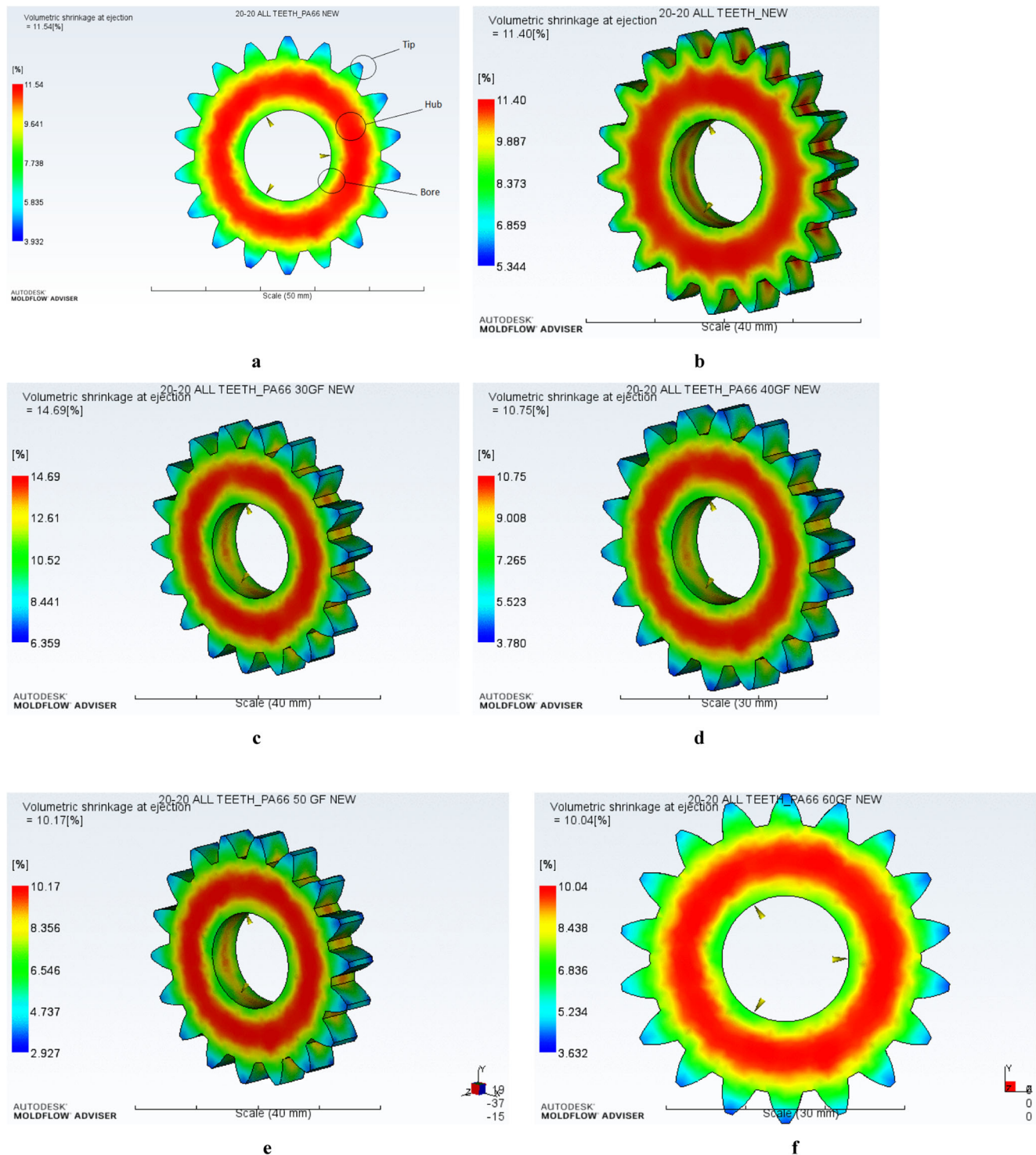
H high, P present, L low, NA not applicable



**Fig. 7** (a–e) Average fiber orientation tensor for 20–20°, 20%, 30%, 40%, 50%, 60% glass fiber–reinforced PA66 respectively

The effects of volumetric shrinkage on major gear dimensions of unreinforced and glass–reinforced PA66 gears are shown in Fig. 9.

In the case of glass fiber–reinforced gears, all the measured parameters indicate less deviation than unreinforced gears due to the reduced shrinkage by the presence of



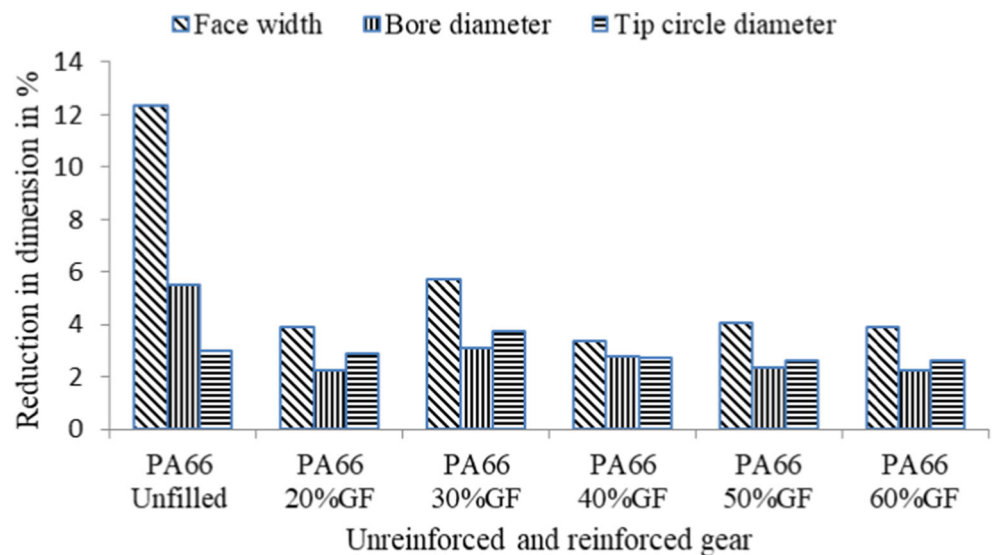
**Fig. 8** (a–f) The volumetric shrinkage for 20–20°, unreinforced, and 20%, 30%, 40%, 50%, 60% glass fiber–reinforced Nylon 6/6 gear

glass fibers. However, for the same gear material PA 66 unreinforced and reinforced PA66, each measured parameter shows a deviation from the design value due to the difference in fiber orientations.

When fibers are oriented in the radial direction along the tooth of the gear, less shrinkage is observed at tip circle diameter of gears [23]. Hence, the deviation of tip circle diameter for reinforced PA66 gear from designed values is less in



**Fig. 9** Variation in gear dimensions in unreinforced PA66 and glass fiber–reinforced PA66 gears



comparison with unreinforced PA66 gear. The region that is located near injection points contributes to less shrinkage due to more packing pressure. Therefore, bore diameter shows less deviation. However, molded gears with reinforcement show less deviation for critical dimensions of gears.

It is also seen that for unreinforced and reinforced gears, shrinkage at the gear tooth tip is less. However, more shrinkage is observed in the case of hub and bore section as shown in Fig. 8a. The same type of variation is seen for different glass fiber contents. The simulation study will hold good if the percentage of error is varying in range of less than 5% [24, 25] for structural and less than 20% for composite matrix [26, 27].

### Simulation with ANSYS Workbench

The current trend of Industry Internet of Things (IIOT) has further demonstrated the importance of simulation precisely with solvers such as ANSYS, ABAQUS, NASTRAN, LS-DYNA, RADIOS, and OptiStruct [28]. A symmetric spur gear CAD model is converted to neutral file form of STEP and

imported into ANSYS Workbench platform [29]. The details of simulation were discussed in the future aspects.

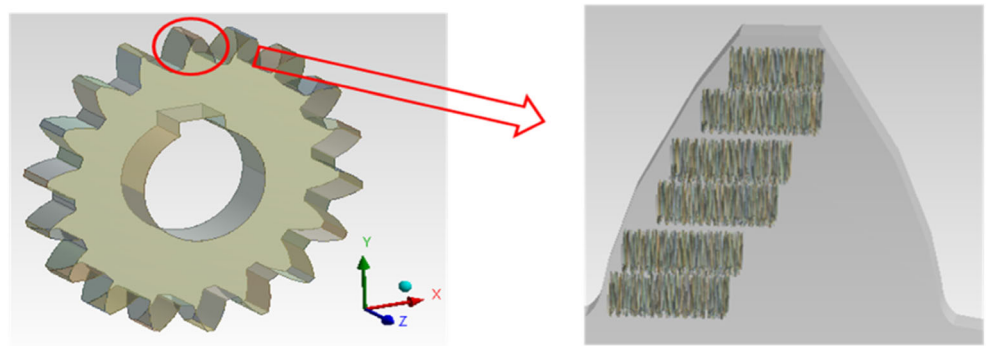
### Geometry

From Fig. 10, it is inferred that the whole spur gear follows the axi-symmetric boundary condition. This makes the CAE model more simple and easier to solve considering a single tooth for analysis.

### Contact generation

Figure 11 illustrates the contact generation between the glass fiber and PA66 substrate. For the optimal case of volume fraction, the simulation model was developed with the assumption that the material behaves in an isotropic manner, with all the fibers oriented outward to the tooth profile. Each of these fibers was created with bonded contact (similar to welding condition or permanent joint). The contact behavior is maintained with “pure penalty approach” as these fibers will not penetrate the substrate; they are physically separate and bonded together with adjusting to touch condition [30, 31].

**Fig. 10** CAD model imported in ANSYS platform with unit gear tooth



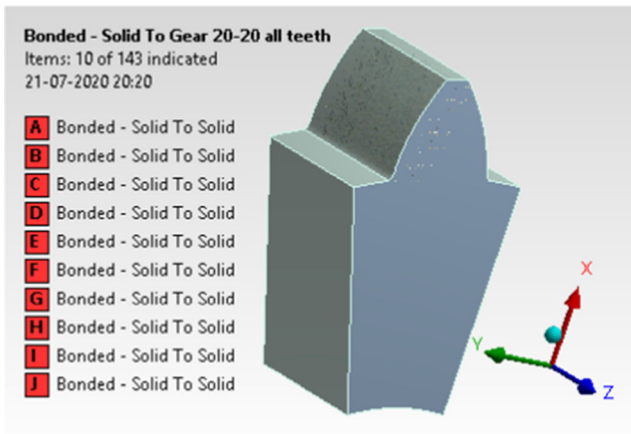


Fig. 11 Mesh generation inside/outside the gear tooth

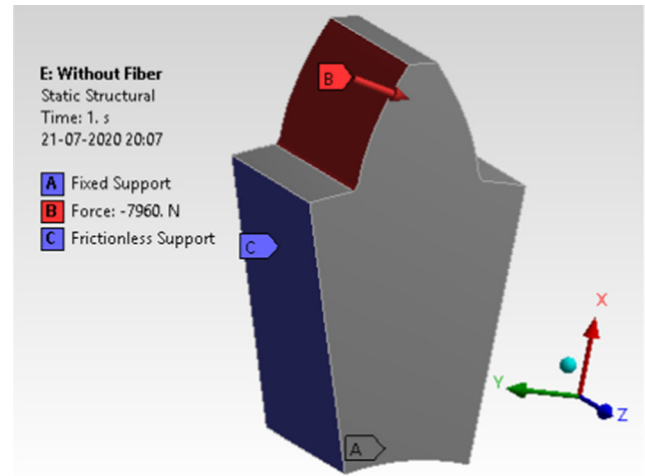


Fig. 13 Loads and boundary conditions for the gear tooth

**Mesh generation**

Figure 12 depicts a wireframe model with fibers, and the adjacent image covers the full mesh structure with “Tetrahedron” element in ANSYS; it depicts SOLID 187 [32] with 10-node element for second-order condition. The details about nodes and elements were highlighted in Fig. 12.

**Loads and boundary conditions**

From Fig. 13, it is inferred that the unit gear tooth is subjected to a load of 7.96 kN, and notation A shows the entity is fixed at a particular location. On either side of the tooth, frictionless support is considered which means its symmetric boundary conditions as well as the number of teeth are still available on both sides.

**Total deformation**

Figure 14 presents the results with fiber and without fiber conditions. The correlation did illustrate the variation with fiber and without fiber conditions. The fibers were able to reduce the deformation in the case of with fiber and it reduces

the deformation rate by nearly 20% [33]. This will have an impact on increasing the fatigue life of the gear tooth and durability of each tooth for long life. Checking the convergence criteria used the H-type and P-type methods focusing on element size and element order.

**Conclusions**

From the present study:

- Symmetric spur gear tooth profile can be easily generated by using the equations presented in earlier chapters. Later involute profiles can be used to create 3D model of gears and illustrated for finite element analysis.
- Fiber orientation, volumetric shrinkage for unreinforced PA66 and glass-reinforced PA66 molded gear, and major dimensions of gear such as tip circle diameter, face width, and bore diameter were measured, and deviations of these parameters from designed values are studied. The result obtained from mold simulation tool indicates that fiber orientation tensor for different glass fiber contents in PA66 gear profiles was found close to unity.

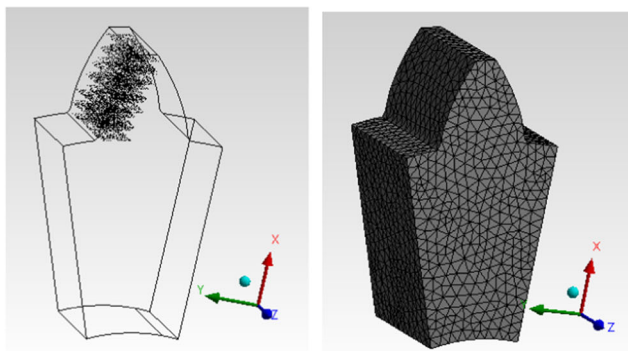


Fig. 12 Mesh generation inside/outside the gear tooth

Statistics	
<input type="checkbox"/> Nodes	5331366
<input type="checkbox"/> Elements	2463394

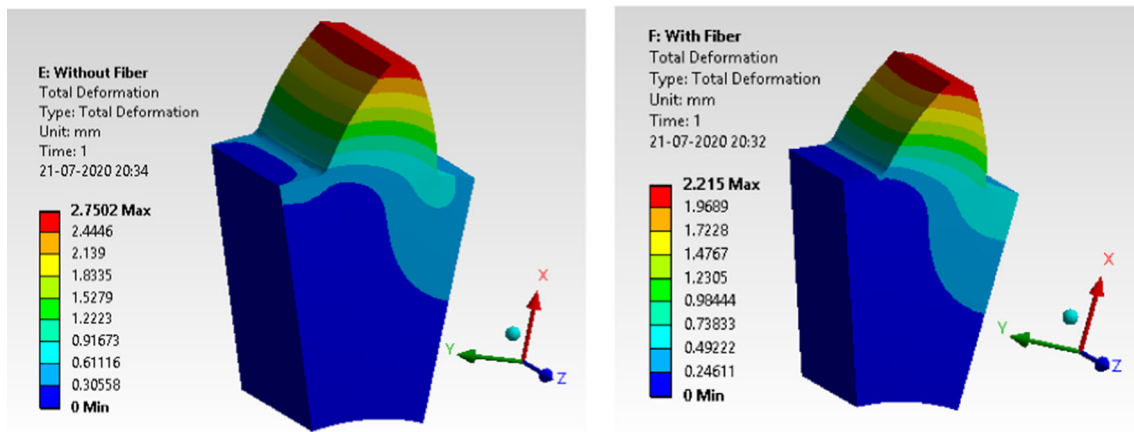


Fig. 14 Mesh generation inside/outside the gear tooth

- Inclusion of glass fibers in PA66 resin decreases the overall volumetric shrinkage in molded gears. The presence of glass fiber gear leads to less deviation of involute gear profile of reinforced gear when compared to unreinforced gears.
- The finite element analysis illustrates a reduction of 20% deformation from without fiber case to with fiber case. This will definitely increase the durability and life of the entire gear.

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