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Polyamide Worm Gear: Manufacturing and Performance

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The focus of this paper is to establish a characterisation method for seven polyamide (PA) grades to determine the major material to manufacture an automotive worm gear. The composite properties were measured according to the worm gear loadings: tensile strength, Young's modulus, abrasion and impact resistance. They were also correlated to the PA moisture absorption and its glass fibre (GF) reinforcement. The data from mechanical tests were applied in the finite element analysis (FEA) using the von Mises stress criterion. Before the rig tests of the PA worm gears, the injection process was evaluated, through the capillary rheometry. A higher difficulty to process PA 6/6 30% GF was found, due to its lower apparent viscosity. In the end, the influence of moisture absorption was as decisive to the gear's material selection as the GF to the pinion. Thus, the PAs with the best performance were: PA 6 with 30% GF (gear) and with PA 60% GF (pinion).

Keywords: *polyamide composites, worm gear, material performance*

1. Introduction

Worm gears are usually made of metallic materials, demanding constant lubricating to minimise the loss of power due to the sliding and also to avoid their corrosion under hostile environments. This statement took Rakic[1] to develop a selection procedure for lubricating oils to avoid gear failure. However, Mao[2] focused his work on the rolling and sliding contact behaviours, using the non-linear finite element analysis (FEA) techniques for carbon steel spur gears machined.

Thermoplastics polymers can be injection moulded as gears, being recycled and either applied without lubrication, but it does not mean no sliding wear or no overload during the power transmission. For instance, polyamide (PA) 6/6 glass fibre (GF)-reinforced gears have been used as a driven gear running against AISI 8620 steel driver gears, measuring the temperature and the teeth profile for the wear analysis[3].

Although the GF reinforcement of PA 6/6 has increased the stiffness and the tensile strength, the wear due to sliding is more compromised in composites than in pure PAs, as studied by Wright and Kukureka[4]. La Carrubba et al.[5] nevertheless, presented another important requirement to polymer gears: dimensional stability, in this case, due to the lower volumetric expansion coefficient of PA 6 GF composites.

A worm gear cinematic implies varied efforts on the gears' teeth. Relative movement is not pure rolling, sliding occurs between gears' teeth, which causes the loss of efficiency and lower power transmission[6]. Determined requirements are analysed by other authors to find the major material for polymer gears. Kurokawa et al.[7,8] selected the poly-ether-ether-ketone (PEEK) composite gears varying the carbon fibre (CF) reinforcement and lubricating conditions to bending fatigue stress and weight loss criteria. Senthilvelan and Gnanamoorthy[9] analysed the PA 6/6 composites, varying the GF and CF reinforcement for spur gears, without lubricating, observing more heating during gears engagement in the last combination.

For the present study, seven PAs were pre-selected and evaluated as the worm gear material originally made of lubricated AISI 8620 metal used in a truck spare wheel holder. The worm gear performance was evaluated in a test rig, simulating the real application of these polyamide gears.

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PAs are hydrophilic; therefore, they were tested before and after heat treatment with boiled water. There were no previous references of the moisture effect in the mechanical properties for PA composite gear applications; in general, studies[9] about PA gears considered their properties as dried materials, even when analysed by FEA or in the operational condition.

The seven PAs were first analysed to obtain their mechanical properties data, in order to determine the GF and moisture effects on these materials. The second step was the FEA, filtering three PA composites. The rheometric analysis pointed two PAs, according to the manufacturing requirement, to finally run three worm gear combinations of these two materials in rig tests.

2. Experimental

Commercial thermoplastic polymers were chosen among the PA families, as they are usually applied as engineering plastics.

The filler content is a path to improve mechanical properties of PAs[10]. The PA 6 and 6/6 were employed in the present work without reinforcement (pure) and with GF varying in two grades: 15 and 30% of GF weight. A branched PA sample with 60% GF was also used. Seven PAs were analysed in total. The PA suppliers were: PA 6 (brand name: PRIMID, Mazzaferro - Brazil); PA 6/6 (brand name: ZYTEL, Du Pont - Brazil) and PA branched (brand name: TECHNYLSTAR, Rhodia - Brazil).

In the laboratory, the temperature of 23 ± 3 °C, also the relative moisture of 50 ± 5% and the pressure of 96 ± 10 kPa were kept constant, in order to execute the experimental tests as follows.

2.1. *Test specimen preparation*

The test procedures and specimen dimensions followed the ASTM standards: Tensile Strength[11], Izod Impact[12] and Abrasion[13]. Specimens were moulded in a hydraulic injection machine (Himaco model LH150–80) of approximately 150 kg of mass injection capacity and 800 kN maximum closure force. All materials were prepared using the operational parameters of the injection moulding machine listed in Table 1.

The water absorbed by PAs can produce bubbles in the melt, affecting thus the homogeneity, the manufacturing process, the mechanical properties and the final dimensions of moulded test specimens[14]. Therefore, the PA samples were dried for 8 hours at 80 °C in an oven prior to injection moulding.

2.2. *Physical tests*

The PAs were tested with and without heat treatment according to the item 7.5[15]. This standard specifies the PAs' heat treatment, which consisted of immersing the PA specimens in boiling water for 2 hours. The moisture effects were analysed only in the following tests: tensile strength, impact resistance and abrasion.

The physical tests were performed with five repetitions each material tested to achieve the respective standard deviation.

The universal material testing machine Emic, model DL2000 and with 20 kN of force capacity was used for tensile tests, which includes Young's modulus and tensile strength measurements, conform to the dimensions of the Type I specimen.

The Izod impact testing was accomplished by a CEAST machine model 6545/000, having 7.5 J of hammer energy, with an impact velocity of 3.46 m/s. The B notch was V-shaped in a 45° angle.

The abrasion testing was executed in an abrasion machine model AGPi. The specimen was pressed under 5 N compressive loading on an Alcar P60 emery cloth, running a distance of 20 m.

2.3. *Finite Element Analysis (FEA)*

An FEA model was created to analyse the stress behaviour of the three dimensional model showed in Figure 1. The worm gears' behaviour was considered as a quasi-static system; therefore, the von Mises stress was accomplished. The CAD model was generated in the Solidworks™ software in parasolid extension and exported to the simulation in the ANSYS™ software.

The mesh shown in Figure 1 has 97,641 tetrahedral elements, each with 10 nodes. The same element type was successfully applied in an FEA for spur gears, according to Wang et al.'s[16] method. The symmetric contact elements

Table 1. Injection moulding parameters.

Parameters	PA 6	PA 6 15%GF	PA 6 30%GF	PA 6/6	PA 6/6 15%GF	PA 6/6 30%GF	PA 60%GF
Injection period (seconds)	4.5	5	6	4.5	5	5	5
Cooling period (seconds)	23	22	20	22	18	20	20
Injection pressure (%)	35	40	40	50	40	45	25
Flow pressure (%)	70	80	70	70	80	80	50
Discharge delivery II (%)	30	35	40	40	40	40	40
Flow pressure II (%)	70	70	80	70	80	80	50
Dosage (rpm)	90	90	90	50	100	100	100
Flow (%)	80	80	80	80	80	80	80
Nozzle temperature (%)	40	30	60	25	50	40	60
Temperature of zone 1 (°C)	250	250	250	280	280	280	230
Temperature of zone 2 (°C)	230	230	230	270	270	270	220
Temperature of zone 3 (°C)	210	210	210	260	260	260	210

groups were used to modelled the contact nonlinear in tooth contact zones. Two pairs of teeth are in double contact zone, where the distance is given to the transverse base pitch of gear.

The data of mechanical tests were used as input data to the static analysis. According to the loading conditions, the pinion is restrained from rotation by the internal region and a torque input load from 0 to 19.8 N.m was applied to the gear from 0 to 1 second.

This case represents the worst situation this mechanic system will be submitted in a similar practical situation. The model simulations provided a pre-analysis of the worm gear performances, filtering the materials to the next stage, the manufacturing analysis.

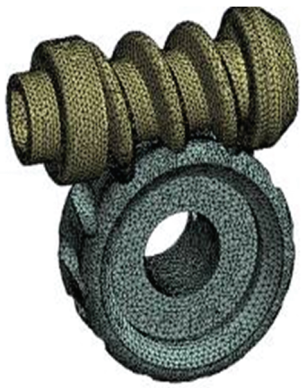
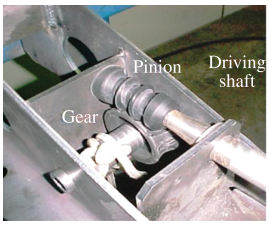


Figure 1. Worm gear meshed model. Source: A. L. Gasparin, L. L. Corso, E. K. Tentardini, R. C. R. Nunes, M. M. C. Forte, R. V. B. Oliveira.



Worm gear:	Pinion	Gear
Teeth number	1	12
Preassure angle	30°	
Helix angle	11,8°	
Face width	75 mm	31 mm
Pitch diameter	26,4 mm	66 mm

Figure 2. Worm gear assembly in the spare wheel holder and worm gear dimensions. Source: A. L. Gasparin, L. L. Corso, E. K. Tentardini, R. C. R. Nunes, M. M. C. Forte, R. V. B. Oliveira.

Due to the small deformations, the consideration of viscoelasticity has been linearized on the Ansys™ software.

2.4. *Performance during Injection moulding*

Moisture is not desirable when PAs are processed; therefore, the apparent viscosity had been performed with dried materials in an oven. The same procedure had been done to the injection moulding specimens.

Apparent viscosity (η) is related to shear stress (τ) and shear rate (γ') by the Rheological Equation of State ($\tau = \eta \, . \, \gamma'$). Injection flow has been compared to the apparent viscosity, which is the parameter to the processing ability. Through the capillary rheometer tester, model Kayeness Galaxy III, the specimens were tested at the injection moulding temperature, for PA 60%GF and PA 6 30%GF, at 230 °C and for PA 6/6 30%GF at 275 °C.

2.5. *Test rig*

The PA worm gears were machined according to Figure 2 dimensions. The gear specimens were assembled in the test rig, which is the truck's spare wheel holder controlled by an electric motor and switches.

The electric motor with a nominal power of 1119 W and a rotational speed of 29 rpm had been used to move the spare wheel up and down in a vertical distance of 370 mm, see Figures 3a, b. The cycle period is 134 seconds and 132 kg the wheel mass. The aim of the rig test is to apply the operational conditions to the PA worm gear samples to determine the cycles that the gears could resist without damage wear and loss of function.

The polymeric worm gear needs to support at least 360 cycles, according to its warranty and application, which means ten years changing spare wheel three times per month[17].

The test rig was the last step to the gear material selection, due to its approaching of the worm gear application and the spare wheel holder self-locking mechanism.

3. Results and Discussions

The worm gears are used to transmit power transmission in perpendicular axles, which imposes 3D efforts, including the sliding problem. Thus, the failure analysis was related to their mechanical and wear resistance. In this paper the

(a) (b)

Legend:

1. Spare wheel holder
2. Spare wheel
3. Cable
4. Test rig
5. Driving shaft
6. Counter
7. Motor

Figure 3. Test rig for the PA composite gears, cycling: spare wheel stand position (a), tyre change position (b). Source: A. L. Gasparin, L. L. Corso, E. K. Tentardini, R. C. R. Nunes, M. M. C. Forte, R. V. B. Oliveira.

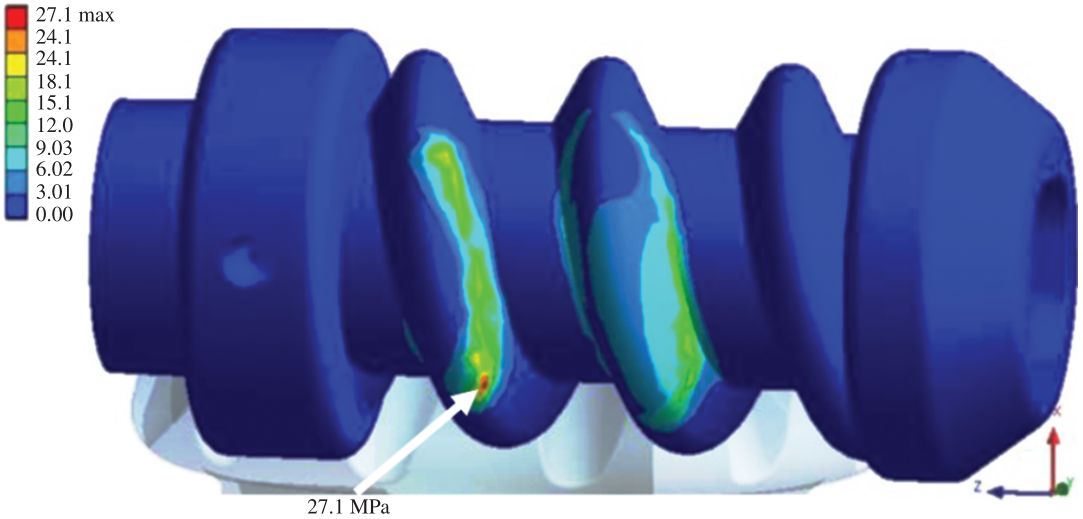


Figure 4. Pinion stress distribution. Source: A. L. Gasparin, L. L. Corso, E. K. Tentardini, R. C. R. Nunes, M. M. C. Forte, R. V. B. Oliveira.

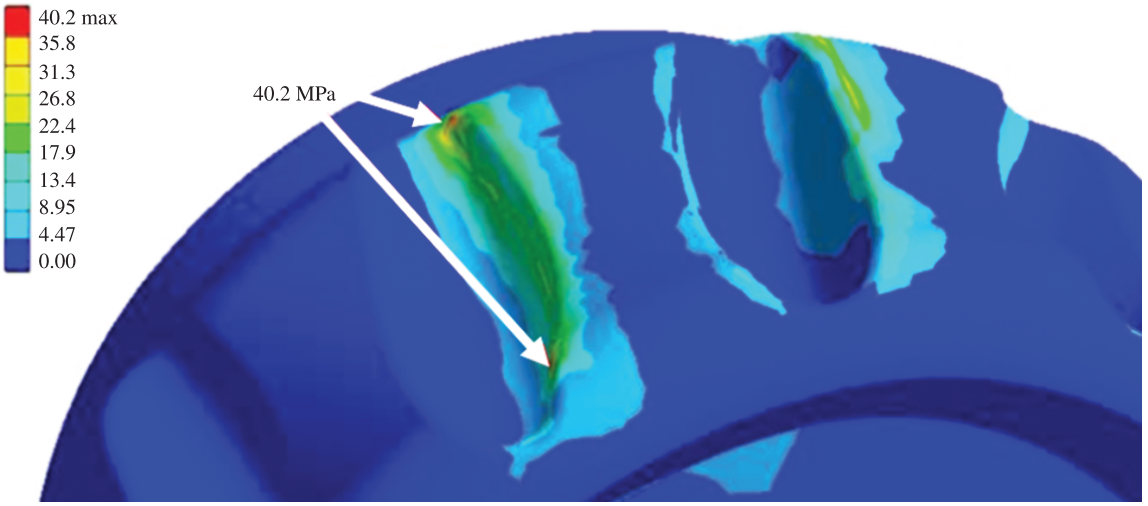


Figure 5. Gear stress distribution. Source: A. L. Gasparin, L. L. Corso, E. K. Tentardini, R. C. R. Nunes, M. M. C. Forte, R. V. B. Oliveira.

manufacturing performance of the injected worm gears was also taken into account, through the injection cycle efficiency analysis, as follows.

3.1. *Numerical analysis*

As pointed by arrows in Figures 4 and 5, the maximum von Mises stress in FEA was 27.1 MPa at the upper pinion tooth and 40.2 MPa at the cavity corners of the gear, respectively. The PAs (treated and non-treated) which can support the allowable stress of 40.2 MPa, considering a design factor of 2 (2 × 40.2 MPa) were the three following: PA 6 and 6/6 both with 30%GF and PA 60%GF. Four PA grades were eliminated using the von Mises stress criterion and their respective tensile strength below the allowable stress (S_{all} = 80.4 MPa), see Figure 6.

Considering the replacement of the truck wheel in a year occurs around 36 times at one period of 4.25 minutes, the spare wheel is moved 2.55 hours during a year. As it is a self-locking mechanism, the worm gear suffers a static loading most of the year. Therefore, the choice for this stress criterion is suitable; once the contact approach analysis is focused also in the period of time where the worm gear is locking the spare wheel, see Figures 3a.

3.2. *Mechanical behaviour*

The mechanical properties were chosen based on the efforts of the gear teeth under movement. Teeth bending can be evaluated by tensile strength, instantaneous torque by impact resistance as well as teeth friction by the abrasion test.

The water acts as a plasticiser, giving more compliance to the PAs. It is shown in Figures 6 and 7 that the heat treatment applied in the PA specimens decreases both the

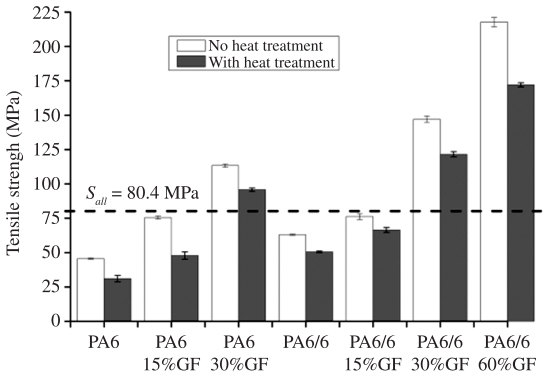


Figure 6. Tensile strength of the polymeric samples. Source: A. L. Gasparin, L. L. Corso, E. K. Tentardini, R. C. R. Nunes, M. M. C. Forte, R. V. B. Oliveira.

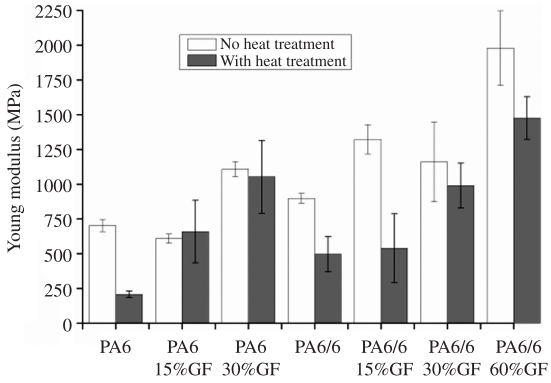


Figure 7. Young's modulus of the polymeric samples. Source: A. L. Gasparin, L. L. Corso, E. K. Tentardini, R. C. R. Nunes, M. M. C. Forte, R. V. B. Oliveira.

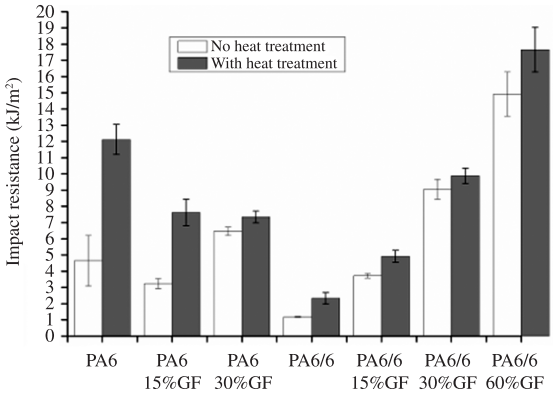


Figure 8. Impact resistance of the polymeric samples. Source: A. L. Gasparin, L. L. Corso, E. K. Tentardini, R. C. R. Nunes, M. M. C. Forte, R. V. B. Oliveira.

tensile strength and elastic modulus, while the GF increases them.

As shown in Figure 6, the tensile strength of pure PA 6/6 is 63 MPa for a non-treated PA, while for the treated one is around 50 MPa. This represents almost 20% of tensile strength loss; such consideration could reprove the material according to the von Mises criteria. Senthilvelan and Gnanamoorthy[9] found the tensile strength of pure PA 6/6 around 76 MPa, but they did not consider the moisture effects.

The heat treatment changed the Young's modulus even in GF-reinforced PAs. The moisture presence decreases the Young's modulus in different scales for PA 6 and 6/6. This gap of stiffness in the PA 6/6 samples, treated and non-treated, is higher on average when compared to the PA 6 samples, because of the hydrogen bonds formed with water molecules occurs according to the respective PA functional group.

A different behaviour happened to PA 6 15%GF, its gap was higher than the PA 6/6 15%GF (Figure 7).

The PAs which presented the highest tensile strength and Young's modulus, in decreasing order, were PA 60%GF (*Technylstar*), PA 6/6 30%GF and PA 6 30%GF, considering the moisture or the heat treatment. As observed by Rajesh et al. [10], the flexural modulus was around 2.5 times higher for PA 6/6 20%GF than for the pure one. The GF reinforcement, therefore, is one path to increase the PAs' stiffness.

There are recent studies involving PA gears with and without GF reinforcement[3,9,18,19], but none of them discusses the moisture influence in the material properties for gear applications. The highest stiffness and tensile strength were the desirable properties for the gear materials. Correlating these properties with the heat treatment effects, the composites PA 60%GF and PA 6 and 6/6 both with 30%GF were pre-selected for the final stage.

The impact strength is similar to the energy absorbed by gear teeth when the gear suffers a sudden loading like when the truck jumps in bumps or holes in the road. The worm gears in this study are a self-locking mechanism, projected to avoid rotation, if there is not external pinion torque application.

Samples with the highest impact strength were PA 60% GF, PA 6, PA 6/6 30% GF and in fourth place PA 6 15% and 30%GF, according to Figure 8. The heat treatment has become an evidence for impact resistance improvement, mainly for PA 6 grades. The higher molecular weight of PA 6/6 contributed to the higher gap between the non-treated and the treated PA 6 specimens, although for PA 6 30%GF such behaviour was not confirmed.

Abrasion resistance was also verified in all PA samples. Sliding always occurs in worm gears and is responsible for mass loss in such components. As seen in Figure 9, the materials with the lowest mass loss or the highest abrasion resistance were PA 6 and 6/6 both pure and the higher mass loss occurred to PA 60%GF specimens. Nevertheless, studies confirmed the reduction of heating during sliding, due to modification of the coefficient of friction. As observed by Kukureka et al.[20], the friction coefficient of the GF-reinforced material (PA 6/6 30%GF) was about half of that found with the same material but with CFs and about one quarter from that of unreinforced polymer.

The presence of GFs increased the mass loss, but the PA heat treatment had no influence on this property (see Figure 9). That was an unexpected result, once the correlated properties, tensile strength; Young's modulus

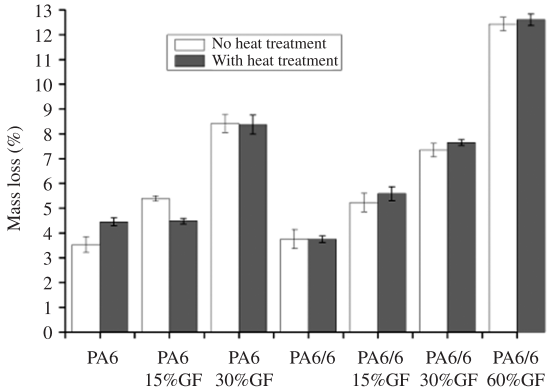


Figure 9. Abrasion resistance of polymeric samples before and after heat treatment. Source: A. L. Gasparin, L. L. Corso, E. K. Tentardini, R. C. R. Nunes, M. M. C. Forte, R. V. B. Oliveira.

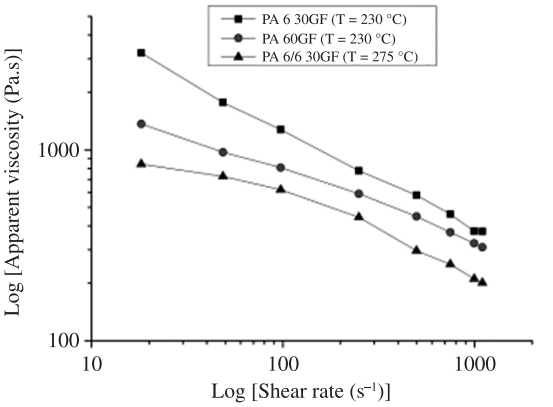


Figure 10. Apparent viscosity versus shear rate. Source: A. L. Gasparin, L. L. Corso, E. K. Tentardini, R. C. R. Nunes, M. M. C. Forte, R. V. B. Oliveira.

and impact resistance were modified by the moisture effect (see Figures 6, 7 and 8, respectively).

The moisture lodges among molecules plasticise the PAs, decreasing the stiffness and modifying the secondary bonds[14]. Following this way, the primary bonds are considered responsible for the abrasion resistance. This also can explain the moisture non-influence on PAs' mass loss in abrasion tests, once it is correlated to intermolecular bonds or secondary ones.

3.3. *Flow behaviour*

In injection moulding, the molten polymer flows through channels producing shear stresses as it undergoes deformations during its journey to the mould cavity. If the polymer viscosity is too low, it can flow around the nozzle blocking the mould cavity. It can increase the injection cycle, because the nozzle must be cleaned periodically, harming the productivity.

The best performance of the material evaluated was considered through lower maintenance of the injection moulding machine. The PA 6 and 6/6 both with 30%GF and PA 60%GF was tested through a capillary rheometer to select two of the three materials analysed in this step.

Figure 10 presents a parameter of selection based on the manufacturing process of injection moulding, the shear rate versus apparent viscosity. It can be seen that PA 6 30%GF has higher values for apparent viscosity at lower temperatures, which determined its choice over PA 6/6 30%GF. The lower temperature implies less electrical energy consumption; higher apparent viscosity implies less nozzle cleaning during the injection cycle.

3.4. *Worm gears' performance on test rig*

The materials tested at this point were PA 6 30%GF and PA 60%GF. The worm gear was designed for the mechanism of a truck spare wheel holder. The spare wheel must be lifted up to the holder and be placed on the floor when the wheel is replaced, according to Figures 3a, b. The test rig results were placed in Figure 11, the failure points were pointed by arrows.

The first choice for the worm gears' materials was the PA 60%GF, due to its highest tensile strength and

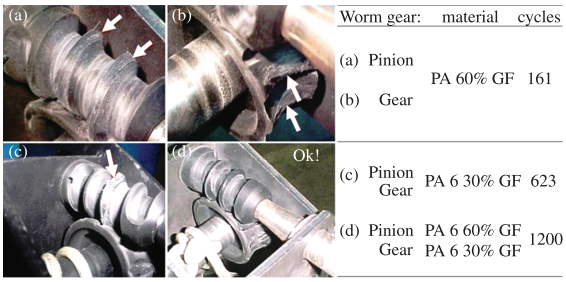


Figure 11. Worm gears after rig tests. Source: A. L. Gasparin, L. L. Corso, E. K. Tentardini, R. C. R. Nunes, M. M. C. Forte, R. V. B. Oliveira.

stiffness. According to function criteria, this combination lasts 161 cycles. The failures appeared in the top of pinion tooth and in the top of the gear tooth cavity according to Figure 11a, b for PA 60%GF worm gears, respectively.

The next option was the gear made of PA 6 30%GF, which failed in the top of pinion tooth after 623 cycles, although the gear integrity was not affected, as can be seen in Figure 11c. Observing the main gear loading, it can be reasonably explained. The pinion suffers bending and its material is the one with the lowest stiffness, therefore, it suffered permanent strain and rupture. For the gear, compression stresses were favoured by the highest impact resistance and the lowest stiffness material.

The last rig test resulted in Figure 11d, the PA 6 30%GF for the gear and the PA 60%GF for the pinion. These materials combine the highest impact resistance for teeth gear cavities and the highest tensile strength for pinion teeth. This worm gear supported 1200 cycles, working without failures.

4. Conclusions

Mechanical PAs' properties and their different scale variations due to GF content and moisture (heat treatment) were the input data to execute an effective FEA. The PAs 6 and 6/6 both with 30%GF and PA with 60%GF were the best samples selected under FEA, comparing tensile strength to von Mises allowable stress.

The apparent viscosity was applied as a selection parameter for the injection moulding process, eliminating the PA 6/6 30%GF for its lower viscosity. Such an approach is not usual to select a polymeric gear, but it seemed to be effective for PAs' selection, when the subject is manufacturing.

Water absorption by PAs in general decreased the stiffness and increased the impact resistance. These properties were correlated to the gear teeth cavities, which suffer mainly compression loading. Heat treatment, however, did not show any significant influence on abrasion tests, while the GF reinforcement increased the mass loss.

The GF content for the PA 60%GF pinion determined its selection, due to its higher stiffness and tensile strength to stand the bending loading. The PA 6 30%GF gear was the material which presented the highest moisture gap, increasing its compressive strength range. Such a pair also presented the best workability, once there were 1200 cycles without failures.

Acknowledgements

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