Bending Fatigue Behaviour and Damage Characterization of Bio-composite Gear

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ABSTRACT

The bending fatigue behavior of a composite gear is assessed. The composite is made of 40% of yellow birch fiber, 3% MAPE and 57% HDPE. Preliminary results show basic mechanical properties comparable to technical plastics. A custom test bench is designed to load a single tooth in bending, to adapt to multiple gear sizes, to adjust the contact point and to minimize the thermal damage. The bench also allows the use of a camera to image the crack progression at the base of the gear tooth and the use of piezoelectric sensors to record acoustic emissions. The statistic lifetime of the composite is plotted, and an endurance limit is found. The damage evolution is evaluated through crack progression, acoustic emission and residual strength. The three damage qualification methods are compared together and between the four displacement loading cases that led to a gear tooth failure. The differences in the damage processes between the bio-composite and the unreinforced HDPE matrix are pointed out.

KEYWORDS: Natural Fibers, Composite, Gear, Fatigue, Damage processes

1 INTRODUCTION

In Mauricie, a region of Quebec province in Canada, the paper industry was once very strong. It changed from 1977 to this day, where multiple factory fusions and closings force the industry to find a way of renewing itself (Bourgeois, 2009) (Montminy, 2014). Coupling to the surge of environmentally friendly design and production trend, the use of residual wood fiber from wood sawing for the reinforcement of plastics is proposed. The great proportion of yellow Birch and the use of the existing industrial installation make Mauricie the place to work on this new material.

Previous works show that young modulus of HDPE reinforced with short yellow Birch fibers is comparable with those of technical plastics like Nylon (Mijiyawa, et al., 2015) (Mejri, et al., 2017). Technical plastics (PA6, PA66, ABS, etc. (Bravo, et al., 2017)), are use for the making of plastic gears and have a cost roughly four times higher than the proposed composite. So, the application to gear is the preferred application to develop the new material.

Even if the mechanical properties are found at the sample scale, the fatigue behavior at gear scale is only partly known (Bravo, et al., 2017) (Mijiyawa, 2018). Five fatigue damage modes are identified, from low to high torque; wear, contact fatigue, root fatigue, superficial temperature and bulk temperature (Bravo, et al., 2015a). The goal of the present project is to cover the root fatigue which is not yet treated by the literature for the current composite. To accomplish root fatigue without dealing with thermal behavior, a custom test bench is design and made to load a single gear tooth in bending.

Firstly, the making of gear samples is presented, starting with the composite fabrication, the gear molding and the preparation of the gear. Then, the test bench is described with his specifications. Afterwards, the three damage indices; the crack length, residual load and acoustic emission, are presented.

This section also includes the respective equipment and consideration for the indices to be relative. The fatigue tests protocol is explained with the different experimental limitations. The results are then separated in two sections, where the first presents the fatigue life and the second presents the damage indices. Finally, a short conclusion sums up the work and shows the different perspective that are yet to come.

2 METHODOLOGY

The methodology section is divided in four parts. The first is about the gear samples making, the second is about specifically designed test bench for single-tooth bending test. Finally, the two lasts parts are about the three damage indices and the proposed fatigue tests.

2.1 Gear Making

Firstly, the composite is made from heating rollers shown in figure 1b. The temperature is fixed to 190°C to melt the matrix without damaging the fibers. The three components are added starting with a small part of the High Density PolyEthylene (HDPE) and the coupling agent (Maleic Anhydride Grafted PolyEthylene (MAPE)). The remaining HDPE is then added with the fibers. Moreover, the composite is mixed three to four times to ensure good uniformity. Finally, the composite (figure 1c) is then removed from the rollers and divided in small pieces.

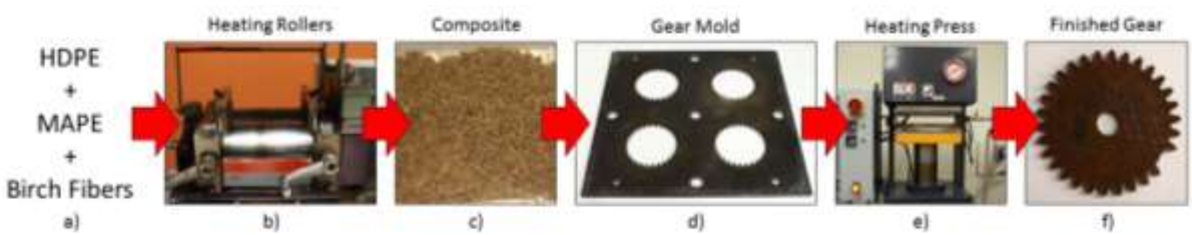

Figure 1: Gear Making

The right amount is weighted and put in the gear mold, shown in figure 1d. The mold is sandwiched between two aluminum plates and two non-sticking silicone mats. The package is placed in a heating press, illustrated in figure 1e, at 190°C. It is pressed at low pressure and then mixed three to four times to remove porosities and ensure a uniform melting. Once well mixed, the pressure is increased to 5.5MPa for 10 minutes. The press is finally water cooled as slowly as possible.

To finish the gear, a hole is drilled in the gear center. Since the gear is not rotating on the test bench, the gear center is estimated with a simple height caliper. One tooth is also removed by abrasion to allow the fit on the test bench. The resulting gear is shown in figure 1f.

2.2 Test Bench

The test bench is specifically made for the present project. It is designed according to reviews of the SAE J1619 standard (Metals Technical Executive Steering Committee, 1997) (Wheitner, et al., 1994). The single tooth loading is an effective way of targeting the bending behavior (Gasparini, et al., 2009) (Handschuh, et al., 2007) (Nenadic, et al., 2011) (Stringer, et al., 2011).

Illustrated on figure 2, the bench is composed of two main parts, the upper one, named the punch, and the lower one, the support. The support holds the gear in place and is adjustable to multiple gear sizes. The gear is locked in rotation by an anvil (shown by a red circle in the figure 2). The anvil contacts the blocking tooth at its base so the breakage always takes place on the tested tooth, which is loaded at its tip. The anvil is supported by a jack to allow the right adjustment to the gear size but also the good adjustment the contact point between the tested tooth and the punch.

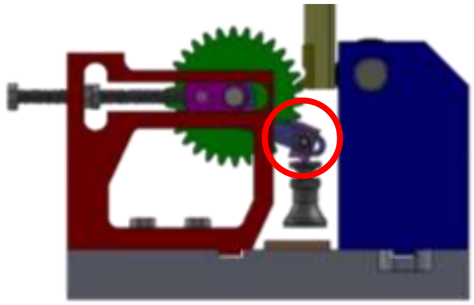

Figure 2: Side view of the test bench

The punch pushes on the test tooth vertically and the action angle of the gear is 20°. So, a portion of the load is applied the roller in the back of the punch, as shown in the schematic view in figure 3. The real force, W, going the gear tooth is linked to the punch applied force, W_t, by the cosine of the action angle θ, as written in equation (1).

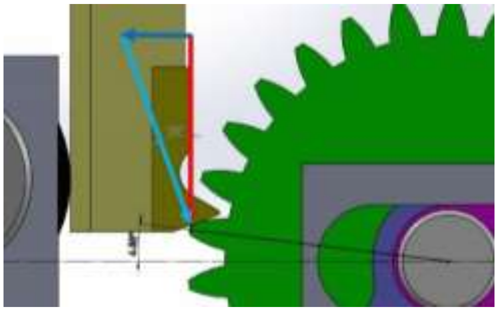

Figure 3: Schematic view of the contact between the test tooth and the punch

$$W = \frac{W_t}{\cos(\theta)} \tag{1}$$

The bench also allows the use of other measurements. The side of the tooth is visible to see the crack propagation and both upper and lower side of the gear is accessible to fix piezoelectric sensors for acoustic emission. The open side access of the tooth is visible in figure 2 and figure 3. For the acoustic emission sensors, figure 4 shows the sensors mounted on the upper and lower part of the gear.

Figure 4: Acoustic emission sensors

2.3 Damage Indices

The three selected damage indices are the crack length, the residual load and the emissions. The three indices are corrected to relative values to enable comparison between them. The crack length is measured via a high definition camera. The camera points perpendicularly to the gear tooth and a ruler is place in the frame to convert the values to mm. The crack is made relative with the thickness of the gear tooth at the crack location.

The residual load is obtained with the load cell on the fatigue test machine. This index is possible because the fatigue tests are controlled via displacement. Therefore, the load will decrease with the increasing cycle number. The fatigue test machine is a hydraulic MTS machine equipped with a 100 kN load cell. The load is read 15 times at each loading cycle to ensure there is a data point near the peak value. The residual load is made relative with the maximum registered value.

The AGMA equation is used to estimate the stress for comparison with our previous works. Since the gear is made of a short fiber composite and is loaded on only one tooth, it is possible to neglect the load sharing factor, K_m, the overload factor, K_o, and the size factor, K_s. The AGMA equation (2) is then reduce to equation (3), where W_t is the tangent load, K_v is the dynamic factor, P_d is the diametral pitch, F is the gear thickness and J is the geometry factor. The values of the different factors are shown in table 1.

$$\sigma = W_t K_O K_v K_S \frac{P_d}{F} \frac{K_m}{J} \quad (2)$$

$$\sigma = W_t K_v \frac{P_d}{F * J} \quad (3)$$

Table 1: AGMA equation related factors

Factors	**Value**
K_v	1,01
P_d	3.9 tooth/cm
F	6.35 mm
J	0.26

The resulting conversion factor is calculated as 0.15538 MPa/N.

The acoustic emissions are harvested through two wide band piezoelectric sensors. A schematic representation of an acoustic signal is illustrated on figure 5. Four parameters are set to acquire data, the peak definition time (PDT), the hit definition time (HDT), the hit lockout time (HLT) and the threshold. Their values are presented in table 2. Those parameters are set to minimize the noise and identify the damages processes (Bravo, et al., 2013) (Bravo, et al., 2015b).

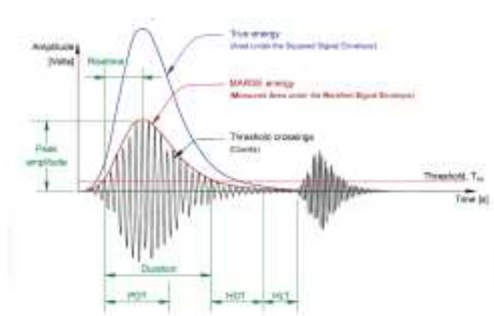

Figure 5: Schematic representation of an acoustic signal (Unnbórsson, 2013)

The damage index is set as the number of counts. This index is chosen because of the influence of the threshold on the energy index. The noise has low energy value, but as soon as the contact between the sensors and the gear is not perfect, only very large events get over the threshold, so not a lot of damage processes are recorded. The count number is more sensible, so a lot of noise can be record, but the noise can be separated from the damage processes by its linear look.

Acoustic emission damage index is made relative with the total number of counts registered during the test. Therefore, this index can only be adjusted at the end of the test and can hardly be use as a real time index for estimating the remaining life of the sample. It can still show damage occurring in real time.

Table 2: Acoustic emission parameters

Parameters	Value
PDT	40 µs
HDT	80 µs
HLT	200 µs
Threshold	30-32 dB

2.4 Fatigue Tests

Fatigue tests are run using displacement as controlled variable. This is done because the estimated force is too low comparing to the 100-kN load cell. The tests are realized on a hydraulic MTS machine. The goal is to obtain lifetimes between 10^5 cycles and 10^6 cycles.

Quasi-static tests are run to estimate the right imposed displacement. Five displacement cases are chosen, they are from 0.46 mm to 0.58 mm by increments of 0.03 mm. The 0.03 mm increment was a minimum to allow the position reset before each test and for each test not to have the same real displacement as another displacement case.

Other loading parameters are set to simulate a real gear loading conditions as close as possible. The loading ratio (D_{min}/D_{max}) is fixed to 0, because a gear tooth is normally completely unloaded when not meshing with the other gear. The loading frequency is set to 10 Hz. This frequency is chosen from previous work (Mejri, et al., 2017) that shows less aggressive damage propagation.

3 RESULTS

This section presents the results of the study. It is split in two. In the first part, the lifetimes of the composite and the HDPE are presented and then compared with the literature. In the second part, the damage processes are compared together and between the two materials.

3.1 Fatigue Life

Life time curves of both materials, HDPE and birch fiber reinforced HDPE, are shown in figure 6 and figure 7, respectively. For both materials, the lifetime is calculated at the crack initiation. The fatigue lifetimes of the HDPE gear teeth show progressive lifetimes. An endurance limit is found at the 0.5 mm displacement case.

For the composite material, the variation at each case is more important. The figure 7 shows the crack initiation data, the Weibull mean value, 5% and 95% distribution lines. The 0.58 mm case has a mean superior to the 0.55 mm case. The same effect is found between the 5% line of the 0.52 mm and the 0.49 mm cases, where the higher displacement has a higher expectancy value. The variation observed at each case is induced by the nature of the composite, where nether the direction nor the concentration of the fibers can be controlled during the molding process.

The stress for each case is calculated according to the steady phase of the residual load. The lifetimes are estimated at the end of the crack progression to allow valuable comparison. It is compared with three points bending fatigue tests (Mejri, et al., 2017) and rotating gear tests (Bravo, et al., 2017). The lifetimes at low stress (20 MPa) are comparable with those of Mejri. Bravo experienced lower or comparable lifetime at 22 MPa compared to simple tooth bending at 25 MPa probably because of the thermal stress added to the rotating tests. At higher stress, the lower lifetimes, compared to Mejri, are caused by the shear and compressive added natures of the stress.

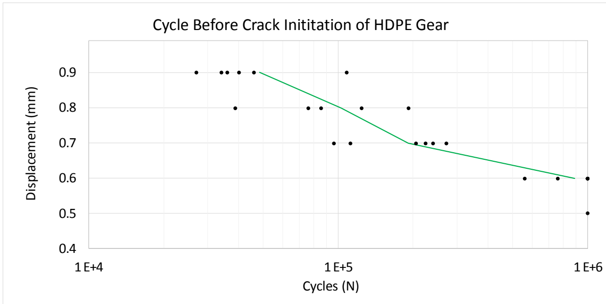

Figure 6: HDPE gear tooth lifetimes

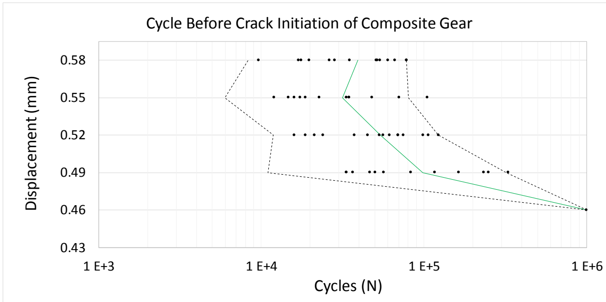

Figure 7: Composite gear tooth lifetimes

Table 3: Literature comparison

Stress	Lifetimes	Autor
20 MPa	inf.	
22 MPa	inf.	Mejri
22 MPa	2.0 E+5	Bravo
25 MPa	2.4 E+5	
26 MPa	1.3 E+5	
27 MPa	6.0 E+5	Mejri
28 MPa	8.3 E+4	

3.2 Damages Indices

The three compared damage indices for both materials are the acoustic emission counts, the crack length and the residual load, all three in relative values. Those are shown in figure 8 for the unreinforced thermoplastic gear tooth at the 0.6 mm displacement case. A representative single test is used to lighten the figure.

There are multiple important points to see in figure 8. Firstly, the three phases in the residual load; the first drop, the steady phase and the final failure. Secondly, all the acoustic activity occurs before the crack initiation. Finally, the crack initiation and progression match the final phase of the residual load.

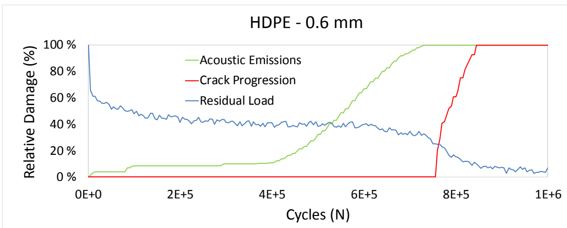

Figure 8: Damage indices for HDPE gear tooth, 0.6 mm displacement case

Figure 9 shows an example of a composite gear tooth at the 0.49 mm displacement case. The same three phases in the residual load observed on the HDPE curve are presents. Most of the acoustic activity is during the crack progression, in contrary to the unreinforced sample. Finally, the crack progression still matches with the third phase of the residual load but is a lot longer.

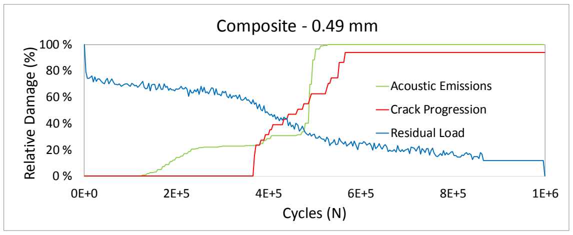

Figure 9: Damage indices for composite gear tooth, 0.49 mm displacement case

The crack progression duration is different for both materials and is easily explicable. Figure 10 shows the difference between crack paths for both materials. As seen, the path for the reinforced gear is less straight. This is due to the presence of fiber forcing the crack to change direction continuously. This also explains why more acoustic energy is observed during the crack progression of the composite.

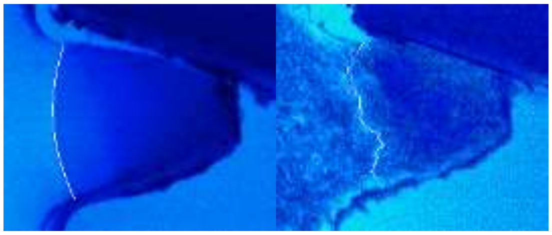

Figure 10: Crack path for HDPE gear tooth (left) and composite gear tooth (right)

4 CONCLUSION

To conclude, the progression from the basic samples to a gear shape sample is an important part for the new material use. The current study shows the application of a short natural Birch fiber reinforced composite to a gear tooth.

The proposed test bench isolates the load on a single tooth and allows the use of different damage measurements. These damages indices are used to compare the fatigue lifetimes and behavior between HDPE and reinforced HDPE. A larger variation is observed for all measurements and lifetimes for the composite and is probably induce by the molding process.

The following step of the project is the modeling of the damage data to quantify the damage on a rotating gear bench and enable the differentiation between the damage causes. The comparison with technical plastic gear is to be planned. Lastly, the transfer to an injection molding press is also a further step to reduce the variation observed in the material. This will also allow the use of the material in its industrial production form.

5 ACKNOWLEDGEMENTS

I would like to thank Université de Québec à Trois-Rivières and the CRSNG for their respective financial support, the I^2E^3 for their facilities and technical support, and the Engineering School of Université de Québec à Trois-Rivières for their facilities.

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