Study of a continuously variable transmission belt made of carbon fiber-reinforced thermoplastic resin

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Abstract

The purpose of this study is to develop automotive frictional parts, especially continuously variable transmission (CVT) blocks using a composite material made of thermoplastic resin and fiber. CVT blocks were used at about 100ºC under high pressure and friction conditions; nylon 9T, otherwise named PA9T, was used. PA9T has a high melting point which is higher than the maximum temperature at the state of slip. To apply composite materials to the manufacture of CVT blocks, material properties such as high strength, modulus of elasticity and fatigue strength are important. Therefore, the aim of this study is improvements in mechanical properties by adding fillers to PA9T under various compounding and molding conditions. PA9T and carbon fibers were mixed using a twin screw extruder. After compounding, dumbbell specimens were made using an injection molding machine. Bending, fatigue and abrasion tests were conducted. Moreover, the transmission capacity of CVT belt made of PA9T composites was evaluated and slip tests were conducted. According to the results of tests, PA9T with CF38.8 vol% achieved desired values for CVT application. The CVT belt has a torque capacity of 40 Nm under an axle load of 2.0 kN.
Keywords: continuously variable transmission belt, nylon PA9T, transmission capacity evaluating test.

1 Introduction

In recent years, global warming, the depletion of fossil fuels and the problem of waste are closing in. Therefore, manufacturing with consideration of the

WIT Transactions on State of the Art in Science and Engineering, Vol 88, © 2015 WIT Press
www.witpress.com, ISSN 1755-8336 (on-line)
doi:10.2495/978-1-78466-167-0/016

environment is important. A thermoplastic resin becomes a liquid by heating above its melting temperature and a solid when it is cooled. Accordingly, it is easy to cast and recycle a thermoplastic resin. In addition, applying a plastic resin instead of a metal, leads to an improvement in fuel efficiency of a car by reducing its weight. Therefore, in this study, the aim is to develop automotive frictional parts, especially continuously variable transmission (CVT) blocks, using a carbon fiber-reinforced thermoplastic resin. CVT blocks are rubbed at about 100ºC under high pressure conditions. Thus, nylon 9T, PA9T, has been used as the base material for the thermoplastic resin [1]. PA9T has a high melting point (304ºC) that is higher than the maximum temperature at the state of slip and high strength among plastics. To apply composite materials to the manufacture of CVT blocks, the requirements of having high strength, modulus of elasticity and fatigue strength are important. Therefore, the purpose of this study is achieving improvements in strength, modulus of elasticity and fatigue strength by adding fillers to PA9T under various compounding and molding conditions. PA9T and carbon fibers (CF) were mixed using a twin screw extruder. After compounding, dumbbell specimens were made using an injection molding machine. Bending and fatigue tests were conducted. Abrasion tests were also conducted because CVT blocks are rubbed under high pressure. Moreover, a transmission capacity evaluating [2–5] and a slip test were conducted on the belt in order to confirm whether or not the mechanical properties of PA9T composites reach the desired values for CVT block application.

2 Experiments

2.1 Specimen

In this study, N1000A (normal grade) and N1001A (antifriction grade) of PA9T (Kuraray-made, Genestar^{TM}) were used. Carbon fiber, CF (Mitsubishi Rayon-made, TR06NE) and boron nitride, BN (Denki Kagaku Kogyo-made, Powder GP) was used as fillers. Table 1 shows the filler contents of pellets. PA9T and CF were mixed using a twin screw extruder (coperion-made, ZSL18). After compounding, dumbbell specimens were made using an injection molding machine (Toyo Machinery and Metal-made, Plaster ET-40V). All pellets were dried in an oven at 80ºC during 24 h before mixing and molding. Table 2 shows the molding conditions.

Table 1: Fabrication conditions for pellets.

Matrix	CF (vol%)	BN (vol%)	Matrix	CF (vol%)	BN (vol%)
N1000A	0	0	N1001A	0	0
	13.7	0		13.7	0
	29.7	0		29.7	0
	38.8	0		38.8	0
	48.7	0		48.7	0
	41.2	7.0		-	-

Table 2: Mixing and injection conditions.

Machine	Setting conditions	
Twin screw extruder	Screw rotation speed [rpm]	150
	Temperature [°C]	330
Injection molding machine	Screw rotation speed [rpm]	150
	Injection pressure [MPa]	150
	Back pressure [MPa]	3.0
	Holding pressure [MPa]	50
	Cylinder temperature [°C]	330
	Injection speed [mm/s]	50
	Holding time [s]	10
	Cooling time [s]	15
	Mold temperature [°C]	120

2.2 Evaluation of mechanical properties

Bending and fatigue tests were conducted to examine whether PA9T has sufficient strength for CVT belt application or not. Fiber length and dispersion were measured to investigate the effects of molding process on them.

A dumbbell specimen was used for the measurement of fiber length. It was cut 4 mm from the center, the resin was evaporated by heating, residual fibers were dispersed in the water and the fiber length was measured by optical microscope. 1000 fibers were measured in each condition.

The center of dumbbell specimen was cut and the cross-section was polished and observed by optical microscope for measurement of dispersion. After fibers and resin were color-coded in the photograph, the latter was divided into n × n bars. All lattices of area rates were measured and standard deviations were calculated. Moreover, the fractal value, that is, the inclination of double-logarithmic graph of standard deviations of area rates with n times –1 was used as index of dispersion. The fractal value is from 0 to 1 and a value close to 1 means good dispersion.

Three-point bending tests were conducted under the testing rate of 2.0 mm/s and span length of 64 mm. The ambient temperature was raised to 120ºC using a high temperature oven. The desired values were a bending strength of 200 MPa and a modulus of 20 GPa.

Fatigue tests were conducted at room temperature. The frequency of the test was controlled at 5.0 Hz. The desired value was a fatigue strength of 60 MPa after 10^7 cycles.

Ring-on-disc abrasion tests were conducted under an axial loading of 1.2 kN and a sliding speed of 50 rpm. Counter materials were S45C and Ra = 0.2 [µm]. Figs 1 and 2 show the shapes of a specimen and a counter material.

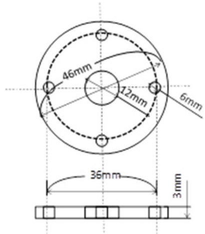


Figure 1: Specimen of abrasion test.

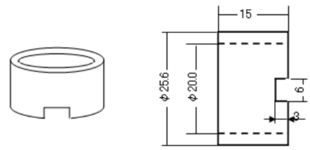


Figure 2: Counter material of abrasion test.

2.3 Assessment of CVT belt capacity

The transmission capacity evaluating and slip tests were conducted to assess the PA9T belt. Fig. 3 shows a schematic of the testing machine. Each testing methodology is described below.

The evaluation of the transmission capacity was conducted to measure the allowable transmitting torque. The test was conducted under tension between pulleys of 980, 1176, 1372, 1568, 1764 and 1960 N and a rotating speed of 5500 rpm. The allowable transmitting torque and the temperature of the belt were measured using a torquemeter and a thermoviewer as driving side torque increased gradually until slip occured. The allowable transmitting torque was a driving side torque at a slip rate of 1.4%. The desired value of transmission capacity was 40 Nm. Also, a running-in was conducted for an hour under zero tension between pulleys and a rotating speed of 5,500 rpm before the test to accustom the contact area to wear.

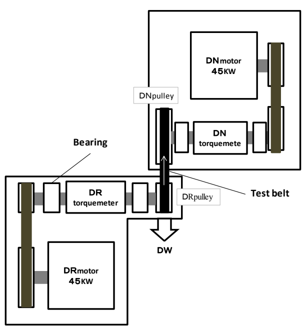


Figure 3: Testing machine for evaluation of CVT belt.

The slip test was conducted to evaluate whether the CVT belt can return to its normal condition after slipping. The test was conducted under tension between pulleys of 980, 1176, 1372, 1568, 1764 and 1960 N, rotating speed 5,500 rpm, driving side torque 40 Nm, and then the CVT belt's capacity to return to normal condition after slipping was checked. The tension between pulleys was increased from 980 N until the melting of CVT belt was confirmed.

3 Results and discussion

3.1 Measurement of fiber length and dispersibility

The fiber length and dispersibility in pellets and specimen were measured. The initial fiber length of CF was 6 mm. Table 3 shows the results of fiber length and dispersibility. According to table 3, the fiber length of N1000ACF48.7 vol% decreased by 85% after compounding with a twin-screw extruder. Also, by molding using a standard or a V and D screw, the fiber length of the specimen decreased by 41% and 30% compared to that of the pellets, respectively. A V and D screw is the screw that can reduce the fiber fracture during plasticization in the injection process. It included a Dulmage zone to improve fiber dispersion. Therefore, the fiber length was shortened by high shear at the Dulmage zone after melting. In terms of dispersibility, the V and D screw was better than the standard screw because high shear stress was sustained.

Table 3: Results of fiber length and dispersibility.

Materials	CF content [vol%]	Fractal Value	Fiber length of Pellets [mm]	Fiber length of specimen [mm]
N1000A	13.7	0.73	0.94	0.71
	29.7	0.81	0.90	0.68
	38.8	0.84	0.88	0.62
	48.7	0.83	0.83	0.61
VandDN1000A	38.8	0.90	0.99	0.58
N1001A	13.7	0.71	0.92	0.70
	29.7	0.79	0.89	0.67
	38.8	0.83	0.88	0.63
	48.7	0.83	0.84	0.60

3.2 Bending tests

Figs 4 and 5 show the results of bending tests at 120ºC. According to these figures, the bending strength and modulus increased as CF contents increase. Bending strength and modulus were less than the desired values by about 20%, that is, a bending strength of 200 MPa and a modulus of 20 GPa in the case of CF38.8 vol%. The bending strength and modulus were better by about 2% and 20%, respectively, than the desired values in the case of CF48.7 vol%. The bending strength and modulus were not improved using the V and D screw. Furthermore, the bending strength and modulus of N1000ACF38.8 vol% increased by 33% and 21%, respectively, and were better by 7% and 2% than the desired values by annealing. Annealing treatment was applied for 2 h under 150ºC. For the specimen without annealing, the mold temperature was controlled at 120ºC. The crystallization temperature of this material is 130ºC. Therefore, annealing at 150ºC increases the crystallization of the specimen.

Table 4: Results of bending strength and elastic modulus.

Materials	CF content [vol%]	Bending strength [MPa]	Bending modulus [GPa]
N1000A	0	26.2	1.3
	13.7	51.1	3.8
	29.7	139.3	11.5
	38.8	162.1	16.9
	48.7	204.0	24.0
VandDN1000A	38.8	160.0	17.0
AnealingN1000A	38.8	215.7	20.4
N1001A	0	30.2	1.3
	13.7	45.2	2.9
	29.7	125.6	10.6
	38.8	162.1	15.8
	48.7	202.0	23.4

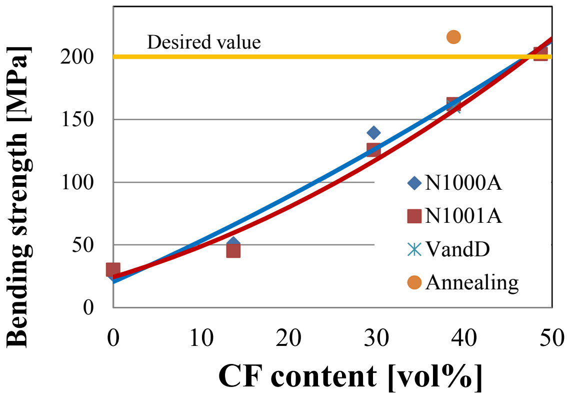


Figure 4: Results for bending strength variation with CF content.

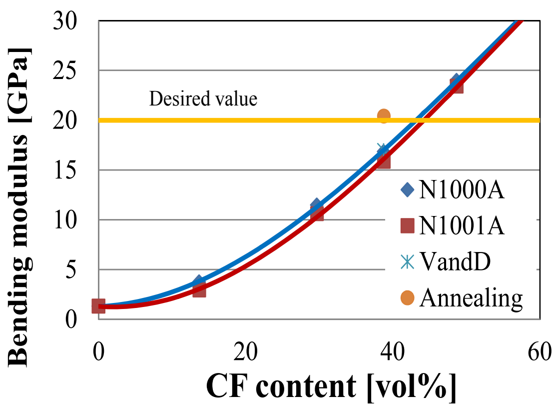


Figure 5: Results for bending modulus variation with CF content.

3.3 Fatigue tests

Fatigue tests of N1000ACF38.8 vol% and 48.7 vol% were conducted. Fig. 6 shows the results of fatigue tests. According to fig. 6, the fatigue strength of N1000ACF38.8 vol% and Annealing N1000ACF38.8 vol% exceeded the desired values. However, the fatigue strength of N1000ACF48.7 vol% was lower. The reason for this is the stress concentration by shaped precision and increased fiber content.

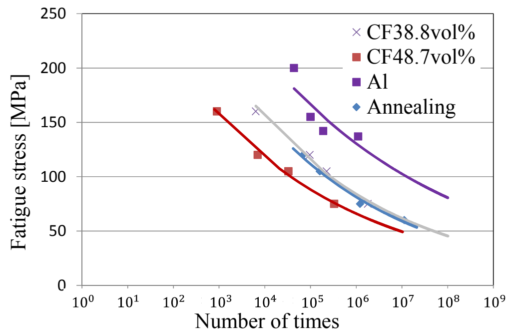


Figure 6: Results of fatigue test.

3.4 Friction abrasion tests

Friction abrasion tests of N1000ACF38.8 vol% and N1001ACF38.8 vol% were conducted. Fig. 7 shows the results of friction abrasion tests. According to this figure, the abrasion wear of N1000A (Normal grade) was less than that of N1001A (Antifriction grade). The wear properties of N1000A were investigated and since the abrasion wear was larger than the desired value, BN was mixed to modify the abrasion wear of N1000ACF38.8 vol%. The abrasion wear attained the desired value by adding BN7 vol%. Thus BN addition not only decreased abrasion wear but also surface temperature by improving wear properties and thermal conductivity [6–10].

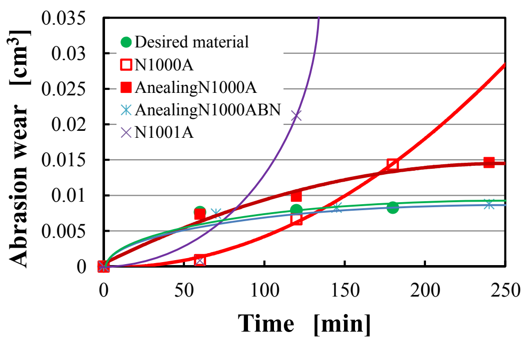


Figure 7: Results of friction abrasion test with CF38.8 vol%.

4 Evaluation of CVT belt

In section 3, the desired property values were attained in bending and fatigue tests. So, an actual CVT belt was molded and its properties were evaluated. The molding of CVT belt was carried out so that the gum was held between blocks; 200 pieces were used after the injection molding of CVT blocks. Fig. 8 shows the shape of a CVT block. The used materials were N1000ACF38.8 vol% (N1000ACF) and N1000ACF41.2 vol% BN7 vol% (N1000ACFBN). Results and discussion of each test are described next.

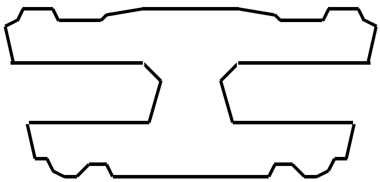


Figure 8: Shape of CVT block.

4.1 Transmission capability tests

Fig. 9 shows the results of the transmission capability test in the form of a graph of slip rate versus the driving side torque; the slip rate increases linearly at the start and non-linearly at a certain driving side torque. The allowable torque is the maximum torque in the linear range. N1000ACF and N1000ACFBN attained a transmission torque of 40 Nm under a tension between pulleys of 1960 N. The transmission torque of N1000ACFBN was slightly higher than that of N1000ACF. Since the CVT belt transfers power by frictional resistance over its contact surface, its transmission capability becomes high when the friction coefficient becomes

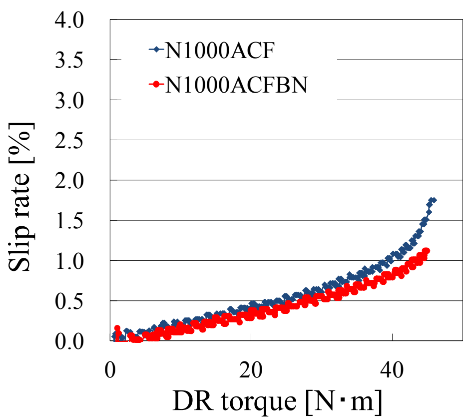


Figure 9: Transmission capability under tension between pulleys of 1960N.

high. However, the friction coefficient of N1000ACFBN was less than that of N1000ACF. To search for what was causing this, the contact surfaces were observed. Worn marks were observed merely at the contact surfaces of the upper beam of both materials and an angle of V of CVT belt was measured. Angles of V of pulley and CVT block were 26º. Table 5 shows the angle, thickness and thermal conductivity of blocks. According to table 5, the V angle of N1000ACFBN was similar to 26º compared to that of N1000ACF. Therefore, the contact area got larger and communicative competence got higher. The reason of this is the fill of upper beam. According to table 5, the thickness of the upper beam of N1000ACFBN is larger than that of N1000ACF. A counterforce that accrues by holding gum between upper and lower beam pushes up the upper beam. As a thickness of the upper beam becomes larger, the hardness becomes larger and the upper beam can prevent bending. Therefore, the V angle can remain near 26º. So the transmission torque of N1000ACFBN is better than that of N1000ACF.

Table 5: Angle, thickness and thermal conductivity of blocks.

	N1000ACF	N1000ACFBN
Angle of V [°]	25.2	25.8
Thickness of uneder beam [mm]	2.45	2.50
Thickness of upper beam [mm]	2.96	3.13
Thermal conductivity [W/mK]	0.893	1.384

Next, the temperatures of the belts are discussed. Fig. 10 shows the temperatures of CVT belts in transmission capability tests. According to this figure, the temperature of the belt was about 49ºC at a driving side torque of 40 Nm. Melting of contact areas was not observed after the tests.

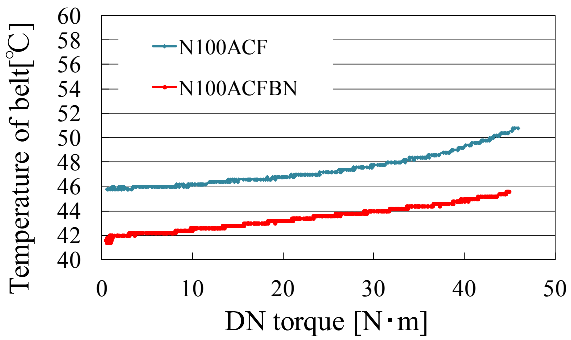
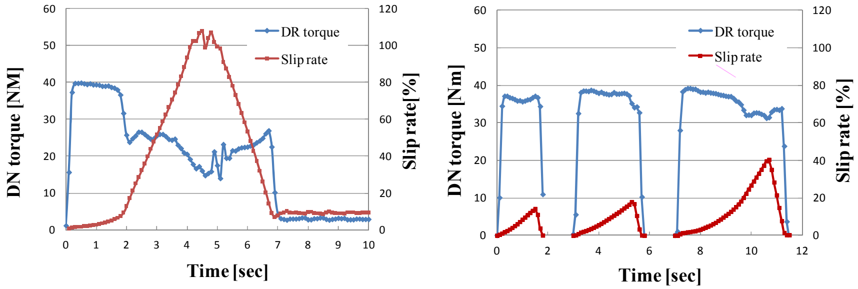


Figure 10: Temperature of CVT blocks in transmission capability test under tension between pulleys of 1960 N.

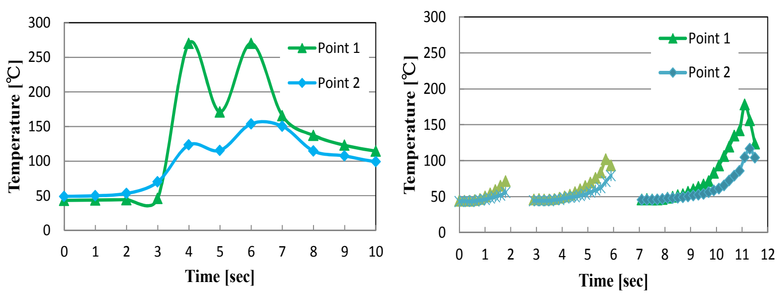
4.2 Slip tests

Figs 11 and 12 show the results of slip tests. Point 1 is the contact area of blocks at the exit driving side pulley and Point 2 is the contact area of blocks at the portal driving side pulley. According to fig. 11, neither material could return to normal conditions after slipping. Neither material could clear the slip test. In the case of N1000ACF, the resin melted in the first test. In the case of the composite with BN, it passed the slip test two times and then melted after three times. Thus, a slip could be prevented by mixing BN into the composite. The reason of this is that V angles become nearly 26° and the contact between pulley and belt becomes better as mentioned in section 4.1. According to fig. 12(b), the slope of slip rate became smaller as the number of tests increased. This is caused by the V angle becoming nearly 26° because of resin wear. Then the cause of melting is the high temperature because of generation of wear heat. According to fig. 12, the maximum temperature decreases by 34% by mixing BN. This causes improvement of not only the friction coefficient but also the thermal conductivity. According to table 5, thermal conductivity increases by 55% by mixing BN7 vol%. The temperature of contact area decreases because the heat moves from the contact area to the center



(a) N1000ACF (b) N1000ACFBN

Figure 11: Results of slip tests.



(a) N1000ACF (b) N1000ACFBN

Figure 12: Temperature of CVT blocks in slip tests.

of CVT blocks due to improvement of thermal conductivity. Moreover, because other surfaces are larger than the contact one, heat transfer to the air became larger by moving the heat to the whole of block and the total temperature of CVT block decreased. Therefore, the slip property was improved by adding BN.

5 Conclusions

There were no differences between the mechanical properties of N1000ACF38.8 vol% and N1001ACF38.8 vol%. PA9TCF38.8 vol% attained the desired mechanical property values for a CVT block. Since the frictional property of N1000A with CF38.8 vol% was better than that of N1001A with CF38.8 vol%, N1000A was used to make CVT blocks. N1000ACF38.8 vol% and N1000ACF41.2 vol% BN7 vol% attained a transmission torque of 40 Nm under tension between pulleys of 1960 N. Also, it turned out that the melting on the slip hardly occurs when BN7 vol% is added because the surface temperature decreased by improving the abrasion resistance and thermal conductivity.

Acknowledgements

The authors thank Mr. Katsuhiko Hata and Katuyosi Fujiwara of Bando Chemical Industries, Ltd. for their advice and Mr. Keiichiro Matsuo and Ms. Yukiko Shirai of Bando Chemical Industries, Ltd. for their help in this work. This work was financially supported by the Program for the Strategic Research Foundation at Private Universities, 2013-2017, MEXT of Japan and Adaptable and Seamless Technology Transfer Program through Target-driven R&D, Japan Science and Technology Agency.

References

[1] Kuraray Genestar™, http://www.genestar.jp/

[2] Kong, L. & Parker, R.G., Steady mechanics of layered, multi-band belt drives used in continuously variable transmissions (CVT). *Mechanism and Machine Theory*, **43**, pp. 171–185, 2008.

[3] Srivastava, N. & Haque, I., Transient dynamics of metal V-belt CVT: Effects of band pack slip and friction characteristic. *Mechanism and Machine Theory*, **43**, pp. 459–479, 2008.

[4] Gauthier, J.-P. & Micheau, P., A model based on experimental data for high speed steel belt CVT. *Mechanism and Machine Theory*, **45**, pp. 1733–1744, 2010.

[5] Julió, G. & Plante, J.-S., An experimentally-validated model of rubber-belt CVT mechanics. *Mechanism and Machine Theory*, **46**, pp. 1037–1053, 2011.

[6] Jeong, S.-G., Lee, J.-H. Seo, J. & Kim, S., Thermal performance evaluation of bio-based shape stabilized PCM with boron nitride for energy saving. *International Journal of Heat and Mass Transfer*, **71**, pp. 245–250, 2014.

[7] Utu, D., Marginean, G., Pogan, C., Brandl, W. & Serban, V.A., Improvement of the wear resistance of titanium alloyed with boron nitride by electron beam irradiation. *Surface & Coatings Technology*, **201**, pp. 6387–6391, 2007.
[8] Mahathanabodee, S., Palathai, T., Raadnui, S., Tongsri, R. & Sombatsompop, N., Effects of hexagonal boron nitride and sintering temperature on mechanical and tribological properties of SS316L/h-BN composites. *Materials and Design*, **46**, pp. 588–597, 2013.
[9] Yi, G. & Yan, F., Effect of hexagonal boron nitride and calcined petroleum coke on friction and wear behavior of phenolic resin-based friction composites. *Materials Science and Engineering A*, **425**, pp. 330–338, 2006.
[10] Steinborn, C., Herrmann, M., Keitel, U., Schönecker, A. & Eichler, J., Correlations between microstructure and dielectric properties of hexagonal boron nitride. *Journal of the European Ceramic Society*, **34(7)**, pp. 1703–1713, 2014.