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VERIFICATION OF MECHANICAL PROPERTIES OF FORGED MOULDING COMPOUND COMPOSITE FOR SMALL STRUCTURAL PARTS OF MICROSATELLITES

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Abstract. The mechanical properties of a short fibre composite produced using the forged moulding compound technology were tested. Firstly, these properties were estimated using analytical calculations and the Tsai-Pagani equation. Next, technological tests were conducted, based on which testing samples were made for mechanical tests. The results of the mechanical tests were then compared to calculations. Finaly, a microsatellite part was produced using this technology and integrated into the satellite structure.

Keywords: Composite, BMC, short fibre, space, satellite, epoxy, carbon fibre.

1. Introduction

Composite materials have found their way into many industries, including space exploration. However, their use here is limited to large structures for launchers and satellites. In small CubeSat-type satellites (microsats) and similar devices, the composites are mainly used as a base material for printed circuit boards (PCBs). This is because composite processing technologies favour large parts. For smaller parts found in the construction of smaller satellites, aluminium alloy parts made by chip machining are preferred. In recent years, the development of composite processing and production technologies has made it possible to achieve competitive mechanical properties even for composites with short to medium lengths of non-oriented fibres.

In general, composites can be divided according to the orientation of the reinforcement fibres into oriented and non-oriented reinforcement, and further according to the length of the reinforcement, into continuous and discontinuous. When producing smaller parts, it is possible to achieve competitive parameters of mechanical properties by using discontinuous non-oriented reinforcements. This makes it possible to produce parts with complex shapes. In terms of mechanical properties, forged moulding compound (FMC) technology appears to be the most effective.

“Forged carbon” (FMC) technology is related to Bulk Moulding Compound (BMC). Unlike BMC, where the reinforcement is mixed with the matrix, the resulting mass is placed in a mould, and then pressed [1], causing the material mixture to flow within the mould. This creep then straightens the fibres in the direction of the flow and the resulting composite does not have isotropic or orthotropic properties. The aim of FMC is to reduce the flow of material in the mould to a minimum and thereby achieve nearly isotropic mechanical properties. In the case of both technologies, the impregnated reinforcement is placed in the mould, which is then closed in the press under increased pressure until the matrix is cured. The mould is often heated to speed up the curing process. The closing of the mould and pressing takes place gradually, thereby achieving a gradual extrusion of the excess matrix from the mould, but not the reinforcement. Knowing the volume of the manufactured part makes it possible to determine the amount of reinforcement and matrix to obtain the target volume fraction in advance, enabling a relatively accurate control. The technology described in [3] is a similar approach, but in the case of FMC, the reinforcement is discontinuous, randomly oriented, and manually placed.

Material	Tensile strength [MPa]
Aluminium alloy	304
Forged carbon	192

Table 1. Maximum tensile strength according to [2].

2. Prediction of mechanical properties

Based on the data from the literature, we expect the modulus of elasticity to be about 10–15 % lower than that of aluminium alloys. The expected tensile strength is presented below in Table 1.

The estimation of mechanical properties can be performed using many analytical formulas such as Tsai-Pagani equation, see below. Although these theoretical calculations can provide a good initial estimation for engineering works, material testing is always decisive.

Using the Tsai-Pagani equation [4], we can predict tensile modulus E using the following process:

$$E = \frac{3}{8}E_{11} + \frac{5}{8}E_{22}, \tag{1}$$

where parameters E_{11} and E_{22} are obtained from Equations (2) and (3), respectively, as shown below:

$$E_{11} = \frac{1 + 2\frac{l_f}{d_f}\eta_L V_f}{1 - \eta_L V_f} E_m, \tag{2}$$

$$E_{22} = \frac{1 + 2\eta_T V_f}{1 - \eta_T V_f} E_m, \tag{3}$$

where parameters η_L and η_T are obtained from Equations (4) and (5), respectively:

$$\eta_L = \frac{\frac{E_f}{E_m} - 1}{\frac{E_f}{E_m} + 2\frac{l_f}{d_f}}, \tag{4}$$

$$\eta_T = \frac{\frac{E_f}{E_m} - 1}{\frac{E_f}{E_m} + 2}, \tag{5}$$

where:

E_m is the tensile modulus of matrix,

E_f is the tensile modulus of the fibres,

l_f is the fibre length,

d_f is the fibre diameter,

V_f is the volume fraction of fibres.

Calculation example for a reinforcement length of 6 mm: Matrix: Hexion MGS285 ($E_m = 3.2\,\mathrm{GPa}$), Carbon fibre: Toray T300 ($E_f = 230\,\mathrm{GPa}$), $l_f = 6\,\mathrm{mm}$, $d_f = 7\,\mu\mathrm{m}$ a $V_f = 0.6$ [4]:

$$\eta_T = \frac{\frac{230}{3.2} - 1}{\frac{230}{3.2} + 2} = 0.959, \text{ [4]} \tag{6}$$

$$\eta_L = \frac{\frac{230}{3.2} - 1}{\frac{230}{3.2} + 2\frac{6}{0.007}} = 0.040, \text{ [4]} \tag{7}$$

$$E_{22} = \frac{1 + 2 \times 0.959 \times 0.6}{1 - 0.959 \times 0.6} \times 3.2 = 16.222\,\mathrm{GPa}, \tag{8}$$

$$E_{11} = \frac{1 + 2\left(\frac{6}{0.007}\right) 0.040 \times 0.6}{1 - 0.040 \times 0.6} \times 3.2 = 137.067\,\mathrm{GPa}, \tag{9}$$

$$E = \frac{3}{8} 137.067 + \frac{5}{8} 16.222 = 61.539\,\mathrm{GPa}. \tag{10}$$

The calculation is analogous for a reinforcement length of 12 mm. See Table 2 for calculated tensile modules.

Reinforcement length [mm]	**Tensile modulus [GPa]**
6	61.539
12	61.950

Table 2. Calculated tensile modules for different lengths of reinforcement fibres.

3. Technological tests

The technological tests began with the design and 3D printing of a closed mould made from PETG material. The mould consisted of four parts: the lower part, two side parts and the upper part (see Figure 1). The upper part, which has a bevel, was closed. After 3D printing, a wax-based release agent was applied to the mould in several layers, then the mould was assembled and ready for the production of the first part.

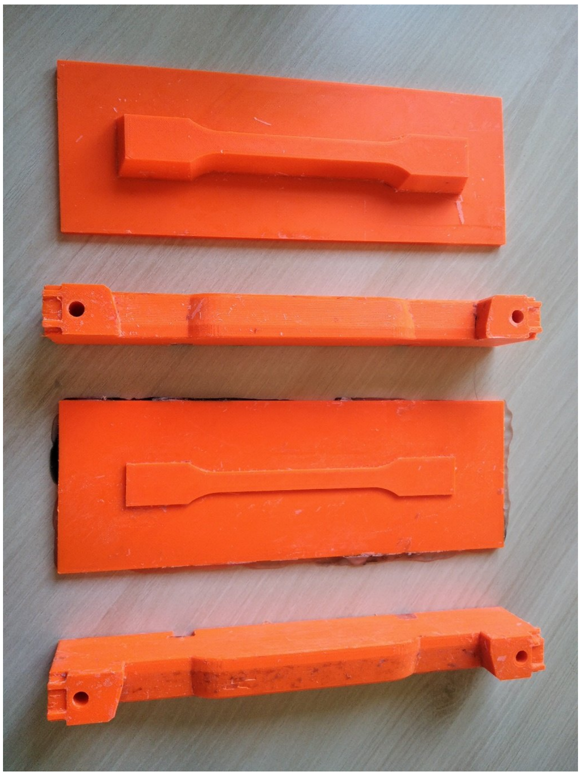


Figure 1. Disassembled mould.

The first parts were made from Hexion MGS 285 epoxy resin and 3 mm chopped glass reinforcement. A target fibre volume fraction (FVC) of 60 % was chosen, for which the exact volume and weight of the required reinforcement portion were then determined, and subsequently the amount of matrix was determined as 125 % of the reinforcement weight. The reason was to achieve the requested shape accuracy and surface quality of the part. Thanks to the gradual increase in pressure when closing the mould and the bevel on the closing part, the excess matrix is allowed to flow out of the mould.

First, a thin layer of matrix was first applied to the bottom of the mould to wet its surface. Then about one-fifth of the dry reinforcement was inserted into the mould, which was then covered with a proportional amount of the matrix. After several repetitions, all the reinforcement and the matrix were uniformly distributed in the mould. This was followed by closing the upper part of the mould and gradually increasing the closing pressure. The pressure was gradually increased in 5–10 minute steps until the mould was completely closed, which took about 30 minutes. After 24 hours, the matrix had cured sufficiently (i.e. it had achieved handling strength) and the mould was disassembled and the part cleaned, see Figure 2.

Figure 2. Process samples with fiberglass reinforcement, 70 % FVC (top) and 60 % FVC (bottom).

Sample No.	**1**	**2**
Theoretical FVC [%]	60	70
Actual FVC [%]	56.3	62.8
Density [$\mathrm{kg\,m^{-3}}$]	1 875.6	1 961.2
Void content [%]	6.5	5.3

Table 3. Results of technological tests.

The actual achieved fibre volume content (FVC) was measured. For the first samples with a theoretical FVC of 60 %, the actual fibre volume content was found to be 56.3 %. The second attempt followed with a theoretical fibre volume fraction of 70 %, where the actual fibre volume content was found to be 62.8 %. For detailed results see Table 3.

The next step were technological tests with carbon fibres measuring 6 and 12 mm in length. Unfortunately, insufficient amount of the matrix caused cavities in these samples. For that reason, the amount of the matrix was increased to 130 % for the next attempt. However, even the increased amount of matrix did not help. The manufacturing process was thus modified, and the matrix was mixed with the reinforcement prior to being placed into the mould. This modification improved the result, the surface quality, and decreased the void content. After adjusting the manufacturing process, the samples for mechanical tests were produced (see Figure 3 for freshly demoulded sample as well as cleaned sample): 5 samples with a reinforcement length of 6 mm and 5 samples with a reinforcement length of 12 mm. In the Figures 4 and 5 respectively are shown samples with 6 mm and 12 mm length of reinforcement before and after the testing was performed.

4. Mechanical testing

The mechanical tests were performed using the Instron 55R1185 universal tensile machine equipped with a 10 kN load cell, and strain was measured using the Instron 3560 extensometer. The tests were performed according to ISO 527-2 standard, i.e. with a loading speed of 1 $\mathrm{mm\,s^{-1}}$, test temperature of 22.4 °C, and a humidity level of 31.1 % RH.

4.1. Test results

Individual test results for both types of the test samples are listed in the following Tables 4 and 5.

4.2. Evaluation of test results

The results show a considerable variance. The significant variation in the measured mechanical properties is probably due to the large differences in fibre orientation distribution between the test samples. It is given by the manufacturing process used, which does not allow it to be controlled. The greater variation coefficient (C.V.) for the 12 mm reinforcement (30.4 %) compared to the 6 mm reinforcement (24.4 %) also supports this hypothesis. The distribution of the orientations of the shorter fibres appears to be closer to that of an isotropic material than the longer ones. The other important factor is also the variation in FVC between the individual test samples.

In order to identify the volume fraction and void content of the test samples, corresponding tests were carried out on two samples from each set. The target FVC of 60 % was not achieved, with a considerable variation in the values obtained for each set. The results are summarised in the following tables. They also contain a comparison of the measured and calculated E-moduli of the individual test samples. The E-moduli were calculated using the approach shown in Section 2 for the measured FVC. For detailed results of test samples see Tables 6 and 7.

The following conclusions were drawn from the analysis of the obtained data:

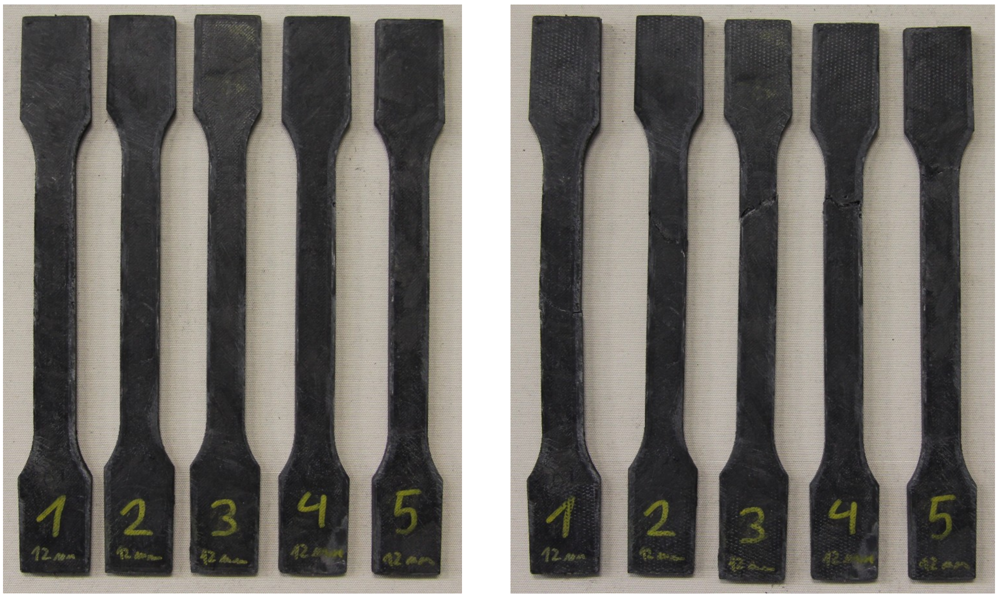
- It was expected that a higher modulus would correspond to a higher strength. However, this relationship was not demonstrated. Although the detailed analysis of the test samples showed the expected tendency, some of the other samples for a given length of reinforcement exhibited the reverse phenomenon. This is probably due to the nature of the randomly distributed reinforcement, which is of finite length and the random overlap of fibres. The modulus measurement was performed using an extensometer with a base of 50 mm, which was placed approximately in the middle of the sample. If sample failure occurs outside this area, the modulus and strength may be completely independent,

Figure 3. Carbon reinforced samples, 6 mm long fibres (top), 12 mm long fibres (bottom), not yet cleaned after removal from the mould.

(a). Before test.

(b). After test.

Figure 4. Specimens with 6 mm reinforcement before test and after test.



(a). Before test.

(b). After test.

Figure 5. Specimens with 12 mm reinforcement before test and after test.

Sample ID	**Failure type**	**Width [mm]**	**Thickness [mm]**	***E* modulus [GPa]**	**Poisson ratio [-]**	**Rm [MPa]**
1	L2	11.52	3.98	41.14	0.178	98.8
2	L0	11.85	3.95	37.54	0.249	94.7
3	Grip	11.79	3.95	42.26	0.448	158.9
5	L2	11.88	4.06	42.58	0.247	106.2
6	L0	11.72	4.03	35.59	0.378	146.7
Avg.		11.75	3.99	39.82	0.300	121.1
S.D.		0.143	0.05	3.097	0.110	29.6
C.V.		1.22	1.28	7.78	36.73	24.4
Min.		11.52	3.95	35.59	0.178	94.7
Max.		11.88	4.06	42.58	0.448	158.9

Table 4. Tensile test result of the samples with 6 mm reinforcement.

Sample ID	**Failure type**	**Width [mm]**	**Thickness [mm]**	***E* modulus [GPa]**	**Poisson ratio [-]**	**Rm [MPa]**
1	L0	12.55	3.88	31.89	0.335	72.0
2	L0	11.87	3.95	64.72	0.117	65.0
3	L0	11.74	4.07	42.28	0.420	134.1
4	L0	11.87	4.13	64.32	0.019	87.4
5	L0	11.99	3.99	57.55	0.426	85.1
Avg.		12.01	4.00	52.15	0.264	88.7
S.D.		0.318	0.10	14.52	0.185	27.0
C.V.		2.65	2.43	27.84	70.20	30.44
Min.		11.74	3.88	31.89	0.019	65.0
Max.		12.55	4.13	64.72	0.426	134.1

Table 5. Tensile test result of the samples with 12 mm reinforcement.

Sample	**Density [kg m^{-3}]**	**FVC [%]**	**Void content [%]**	***E* modulus [GPa]**		**Rm [MPa]**
				Measured	**Calculated**	
6 mm / 1	1 501.5	57.02	3.05	41.14	58.10	98.8
6 mm / 2	1 469.1	51.31	2.85	37.54	51.80	94.7

Table 6. Parameters of 6 mm samples.

Sample	**Density [kg m^{-3}]**	**FVC [%]**	**Void content [%]**	***E* modulus [GPa]**		**Rm [MPa]**
				Measured	**Calculated**	
12 mm / 4	1 456.6	51.24	3.86	64.32	52.15	87.4
12 mm / 5	1 515.6	58.76	2.76	57.55	60.51	85.1

Table 7. Parameters of 12 mm samples.

however, this is also the case when failure occurs in the measured area. As the measured modulus is calculated from the strain of the given section, it is not possible to distinguish local weak points related to reduction in strength.

- An interesting phenomenon is also the different average moduli for both lengths of the reinforcement. The 6 mm reinforcement shows a significantly lower modulus (about 40 GPa) compared to the 12 mm reinforcement (about 50 GPa) at the same FVC. The modulus of the longer fibres is also closer to the predicted modulus values. It is probably due to the orientation of fibres, where the longer fibres were oriented along the longer side of the test sample, while the 6 mm were oriented in multiple directions.
- It was also expected that the effect of porosity on strength would also have a major impact, as the presence of air bubbles in the material can reduce the load transfer from fibre to fibre. However, for the measured range of porosity, it did not have a major impact on the strength value.

5. Verification of the production of the satellite structural part

The next step was to verify the feasibility of manufacturing more complex parts. A structural partition of microsatellite construction was chosen, which is usually milled from an aluminium alloy. Similarly complex parts, produced using the same FMC technology, are used, for example, in sports cars [5]. The design of the mould consists of 6 components due to the complexity of the part. The mould is divided to the base, 4 side components, and the cover. Figure 6 shows the mould already filled with a mixture of reinforcement and matrix. Nine threaded inserts were placed around the perimeter of the part during the filling of the mould. The same type of reinforcing fibres as in previous tests were used and a length of 12 mm was chosen. The matrix system was also the same as that used in previous test, i.e. Hexion MGS 285 epoxy matrix. The target fibre volume content was 55 %.

Once the mould had been filled, the cover was installed, the entire assembly was placed in a press, and pressed until the matrix had achieved handling strength, i.e. for about 24 hours. Subsequently, the part was post-cured at an elevated temperature of 60 °C for 2 hours. Finally, the part was deburred and cleaned, as can be seen in Figure 7.

The finished parts suffered from surface defects, some of these can be seen in Figure 7. However, these can be fixed after demoulding and are not of critical nature. The fibre volume content was not tested for these parts. A mass saving of around 46 % was achieved at around 30 % of stiffness loss compared to the aluminium variant, assuming that target value of 55 % was achieved. These benefits/losses can be further optimised by changes in the FMC part geometry.

The two manufactured parts were implemented in the prototype of a semi-composite microsatellite structure, which is being developed as part of VZLU research activities as shown in the Figure 8.

6. Conclusion

This research involved estimating the mechanical properties of the FMC composite using analytical and experimental methods. Initial screening of the mechanical properties was necessary to verify if the implementation of FMC composite into the microsatellite design is feasible and has a positive contribution. The production of 3D printed moulds was verified during the work on producing test samples and prototype parts. The results of the mechanical tests showed considerable variance and deviations from the theoretical values. The large variance of the measured mechanical properties is probably due to the large differences in the fibre orientation distribution between the test samples. It is given by the manufacturing process used, which does not allow it to be controlled. Nevertheless, the manufacturing of the microsatellite prototype part

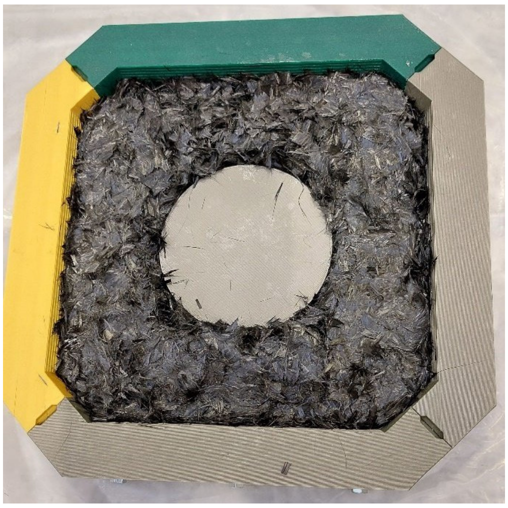


Figure 6. The mould filled with a mixture of reinforcement and matrix.

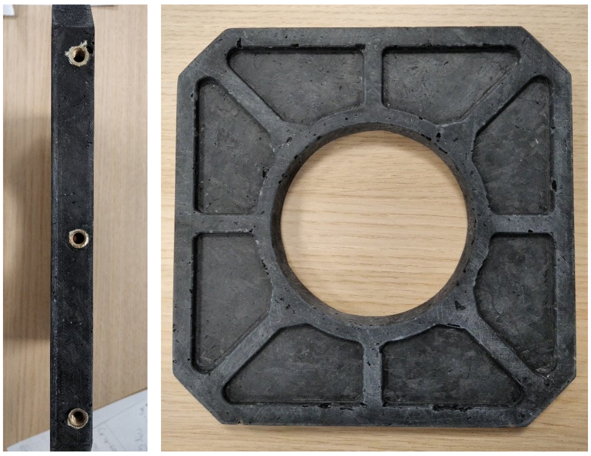


Figure 7. The mould filled with a mixture of reinforcement and matrix.

Figure 8. Parts in the assembly of semi-composite microsat.

has shown significant potential for weight and cost savings for complex shaped parts manufactured using the FMC technology.

There are two possible ways to enable the use of this manufacturing process for microsatellites. The first option is to considerably increase the number of test specimens (more than 15) in order to obtain statistically reliable design allowances. The second option is to improve manufacturing the process to be more predictable. One of the possibilities is to combine the continuous reinforcement and short fibres. The continuous reinforcement (fabric or UD) could be used in flat or simply curved sections and serve as the load bearing member. The short fibres can then be used to fill complex shaped sections, providing bending stiffness and enable the use of inserts for mechanical joints with a surrounding structure.

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