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Tensile Strength of Carbon Fiber

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Abstract: Carbon fiber is a material with a vast area of utilization. When combined with a resin, we get a composite, which provides great mechanical properties, has low mass and can be utilized in many different applications. Carbon fiber cloth can be found in a wide range of forms and shapes, differing from weight to the shape of their weave. Manufacturing a composite part can be achieved with a variety of techniques and processes, each of them having advantages and disadvantages over the other. One of the most common process for producing composite parts is the open moulded hand lay-up process. This process is economically viable, has low cost for equipment, and can produce parts with satisfactory results. A composite sheet is manufactured using the hand lay-up process. Three testing samples are taken out from the composite sheet, and their tensile strength is determined using the ASTM D3039 standard.

Keywords: composite material; hand lay-up; high performance; light weight

1 INTRODUCTION

The composite material produced with the combination of polymer matrix and reinforcement fibers, provides a high-performance composite. The composite material obtained with combination of carbon reinforcement fibers and epoxy-based polymer matrix, can provide the same mechanical properties of conventional materials used in the industry, like aluminum or steel, with the benefit of being lightweight. Carbon fiber composite, compared to aluminum can have a weight reduction of more than 20%, while when compared to steel, the weight reduction exceeds 50% [1]. Because of the weight saving and the rest of the mechanical properties the carbon fiber is primarily used in aerospace and space industries. This material is taking a major progress as well as in the high-end car industry, civil engineering, wind turbine blades and sporting goods [1]. There are large number of companies and research facilities which are running research and development programs to develop processes and technologies for mass production.

To maximize the performance of the fibers in the composite structure, the orientation of the fibers has to be arranged in the direction of the loads, according to the geometry of the part. The fibers can be arranged as a unidirectional configuration in which all fibers are placed in parallel and as a quasi-isotropic in which fibers are placed at 0, 90 and 45° , as presented in Fig. 1 [1].

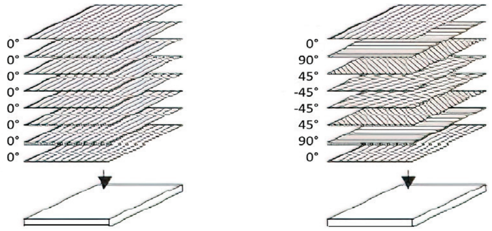

Figure 1 Unidirectional and quasi-isotropic laminates

To take full advantage of the mechanical properties of the reinforcement fibers, it is important to have a high-volume fraction of fibers in the material (55-60%), for the purpose of avoiding fiber curvature of misalignment as well as limiting the void content in the resin (<3%) [1].

There are different types of technologies and processes to manufacture a part from carbon fiber material. These technologies and processes depend of the form of the fibers. The carbon fibers can be found and used in the form of long-fibers, short-fibers or woven in the form of sheets (Fig. 2 [3]). Most promising is the application of the carbon fiber weave in combination with thermoset resins, of which epoxy resins are the most commonly used. Epoxy resin have high mechanical strength, good chemical corrosion and exhibit high performances on elevated temperature of 120 °C [2]. Based on these custom-built sheets complex structures can be produced. The anisotropy and inhomogeneity offer the designer many aspects for structural optimization, but these characteristics also lead to complex stress and strain states within the material.

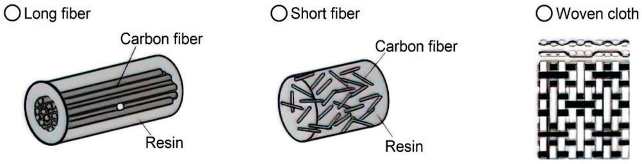

Figure 2 Various arrangements of carbon fibers

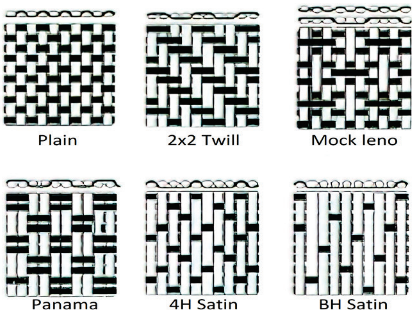

Figure 3 Various types of weaves

The easiest way to manufacture composite parts is hand lamination. For the purpose of reaching high quality its required simple tooling and good manual skills. This process is performed at room temperature. The volume of reinforcement fiber in this process is limited to 40% due to the nature of the process. This process produces a composite part with many imperfections and high void content, due to the lack of vacuum assistance or other type of pressure on the composite part. The reinforcement fibers can be found in a wide variety of weaves (Fig. 3), with different weights and forms, each offering different benefits.

To achieve the best result in mechanical properties, a combination of weaves is required to be used.

2 TESTING METHOD AND MECHANICAL PROPERTIES

The test method determines the in-plane tensile properties of polymer matrix composite materials, reinforced by high-modulus fibers. The composite material forms are limited to continuous fiber or discontinuous fiber-reinforced composites in which the laminate is balanced and symmetric with respect to the test direction. A thin flat strip of material having a constant rectangular cross section is mounted in the grips of a mechanical testing machine and monotonically loaded in tension while recording load. Determining the ultimate strength of the composite material is carried out by testing the maximum load that the composite coupon can carry before failure. By monitoring the strain of the coupon with strain or displacement transducers through the process of testing, a stress-strain curve can be obtained, from which the ultimate tensile strength, Poisson's ratio, tensile modulus of elasticity and transition strain can be derived.

ASTM D3039 provides the minimum requirements for designing a specimen for composite coupons, presented in Tab. 1. These requirements are insufficient for producing a properly dimensioned coupon drawing with tolerances. Therefore, recommendations from Tab. 2 of ASTM D3039 are taken into accord for manufacturing a specimen [4].

Table 1 Tensile specimen geometry requirements [4]

Parameter	Requirement
Coupon Requirements:	
shape	constant rectangular cross-section
minimum length	gripping +2 times width + gage length
specimen width	as needed
specimen width tolerance	±1% of width
specimen thickness	as needed
specimen thickness tolerance	±4% of thickness
specimen flatness	flat with light finger pressure
Tab Requirements (if used):	
tab material	as needed
fiber orientation (composite tabs)	as needed
tab thickness	as needed
tab thickness variation between	±1% tab thickness
tabs	
tab bevel angle	5 to 90°, inclusive
tab step at bevel to specimen	feathered without damaging specimen
See Table 2 from ASTM D3039 standard for recommendations	

This method of testing, provides valuable information for the materials specifications, which are beneficial for research and development, analysis, quality assurance and structural design.

The tensile strength of the composite material is dependent on many factors: type of material, lay-up of the material, preparation, specimen stacking, specimen preparation, specimen conditioning, specimen alignment, the environment of which the testing is conducted, type of grips used on the machine, speed of testing, temperature, void content in the coupon and volume percent reinforcement.

A carbon fiber sheet is manufactured for the purpose of testing the mechanical properties of a composite, who is produced using the hand lay-up process. From the composite sheet, three samples are taken which are used for testing the tensile strength of the composite, dimensions are presented on Fig. 4.

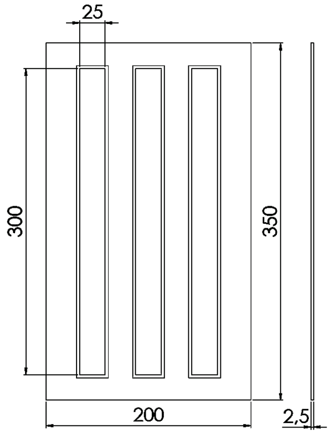

Figure 4 Cut scheme for test samples

3 CARBON FIBER MANUFACTURING PROCESSES

There are many different processes for manufacturing carbon fiber components, varying from manual process of manufacturing, with hand lay-up of carbon fibre cloth, to a more complicated process, using autoclave ovens with pre-impregnated carbon fiber. Each of these processes has its own advantages and disadvantages when compared to another process of manufacturing. A big consideration should be taken beforehand in the requirements of the manufactured part, and choosing the suitable process for the right project.

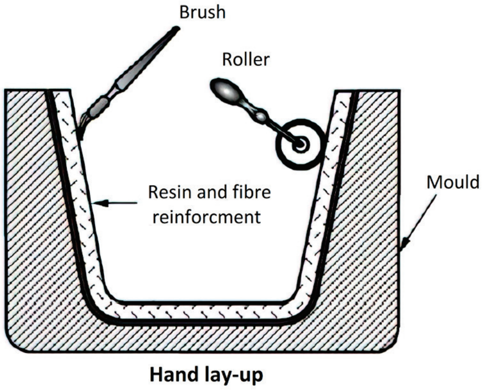

Figure 5 Description of a hand lay-up process

One of the oldest and most common technique for manufacturing carbon fiber components is the open moulded: hand lay-up process, presented on Fig. 5 [7]. This process, has low demands and requirements for tools and environmental conditions, but has a high requirement in the workers skill [6].

The final results achieved with this process, can vary from high grade produce with satisfactory results, to a low grade produce with many imperfections, weak areas (due to excess resin), voids, pin holes, etc., depending on the workers skill.

Hand lay-up process, consists of laying carbon fiber cloth in the mould, and soaking the cloth with a predetermined amount of resin. The wetting of the carbon fiber cloth, can be achieved with a brush, squeegee or a roller. This task is repeated, until the desired thickness of the laminate is achieved.

Before starting the process of hand lay-up of the carbon fiber cloth, the mould surface has to be thoroughly cleaned with acetone, to remove any traces of wax or grease. Also, the mould surface has to be dust free, to prevent inclusions of dust particle in the surface of the part.

To prevent sticking between the part and the mould, there has to be a barrier between these two parts. This barrier is attained with the help of a release agent, which can be: PVA (polyvinyl alcohol), wax, or a suitable chemical release agent. One of the oldest and most common release agents is PVA, which is a release agent dissolved in ethanol. This release agent is commonly used in combination with wax and provides excellent results in releasing the part from the mould.

Peel ply is a woven cloth typically made of nylon, glass or other synthetic materials. This layer of woven fabric, is applied as the final layer of the composite part to provide a porous surface, suitable for adhesive bonding to other surfaces. Other than that, peel ply is used for drawing excess resin from the part, in combination with a bleeder layer.

4 MANUFACTURING OF A CARBON FIBER SHEET

Manufacturing of the composite sheet occurs in a room with low humidity and temperature of 21 °C, which is in the range of the optimal room temperature for producing composite parts.

The carbon fiber sheet is manufactured using the open moulded hand lay-up process. The sheet is made of three individual layers of 12K carbon fiber cloth, who's weave is a 2x2 twill weave pattern, presented on Fig. 6. This weave pattern is composed of tows who go in directions of 0° and 90°, and give an illusion of a diagonal pattern. The 2×2 (also can be found in 4×4 weave) in the name stands for tows going under two tows, and then again over two tows of carbon fibers. This weaving is often used for complex shapes, because of its looser weave, which can be easily manipulated to fit more complex shapes in the mould.

The dimensions of the cloths are 350×200 mm, and approximately 0.6 mm thickness. In theory these layers should produce a ~1.8 mm thick carbon fiber sheet. The fabric to epoxy ratio in this process is 50:50. The weight of the carbon fiber cloth used for manufacturing of the carbon fiber sheet, is approximately 130 g, so the amount of resin used will be about 155-160 g. The amount of resin used is higher due to the method of application with a brush. This is done to prevent a shortage of resin, because of the nature of the brush to soak a small amount of resin. Manufacturing of this carbon fiber can be done in moulds made of a variety of materials, ranging from wood, aluminium, composites moulds to 3D printed plastics moulds.

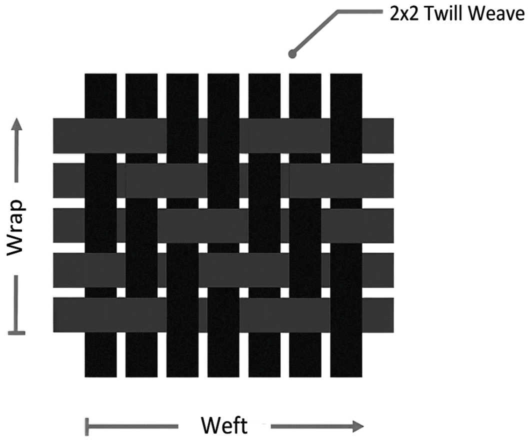

Figure 6 Representation of a 2×2 Twill Weave Pattern

4.1 Manufacturing Process

The manufacturing of the carbon fiber sheet is done on, glass surface which serves as a mould surface, because it provides a flat surface (which allows producing a carbon fiber sheet with a smooth finish), and has no porosity (no need for using a sealant for preventing a mechanical bond between the mould and the carbon fiber sheet). The glass surface is cleaned beforehand with acetone, to remove any traces of grease or dust. A layer of Rexco Formula Five Mould Release Wax is applied using a clean dry cloth, according to the instructions given in the manual. After applying the final layer of wax, the mould is left for one hour for the residual solvents to gas-out before applying PVA. A uniform layer of PVA is applied using a spray gun. After applying the release agent, the PVA is left to dry itself for 10 – 15 min, to create a very thin release film.

The resin used in this process of producing a carbon fiber sheet is SIKA CR-82 epoxy resin, with SIKA CH80-1 catalyst. This resin has low viscosity and is suitable for use in the process of hand lay-up and vacuum bagging where curing temperature more than 75 °C can't be achieved. The mixing ratio of this epoxy system per manufacturer instructions is 100:27 [9], when mixing the two parts by weight.

To reduce the number of voids and pinholes on the surface area on the manufactured sheet, a layer of resin is applied on the mould surface. After wetting the mould surface, a layer of carbon fiber cloth is applied on the surface. The cloth is wetted out using a brush, and the excess resin is removed with the help of a squeegee or a roller. This part is repeated with the remaining layers of carbon fiber cloth. After applying the last layer of carbon fiber cloth, a final layer of peel ply is applied on the composite sheet, and using a roller, the excess resin is drawn out from the part.

After finishing with the stacking of the layers of carbon fiber cloth and finalizing with the peel ply, the carbon fiber sheet is left to cure for 24 hours at room temperature. Additionally, the composite sheet is post cured in an oven for eight hours at 80 °C, Fig. 7 [9]. This is done to acquire a fully cured part, and obtaining the best properties.

Table 2 Properties for HDT and GTT for Biresin CR82 with CH80-1 catalyst

Biresin CR82	ISO Standard	Hardener CH80-1	Unit
Heat distortion temperature	ISO 75A	72	°C
Glass transition temperature	ISO 11357	83	°C

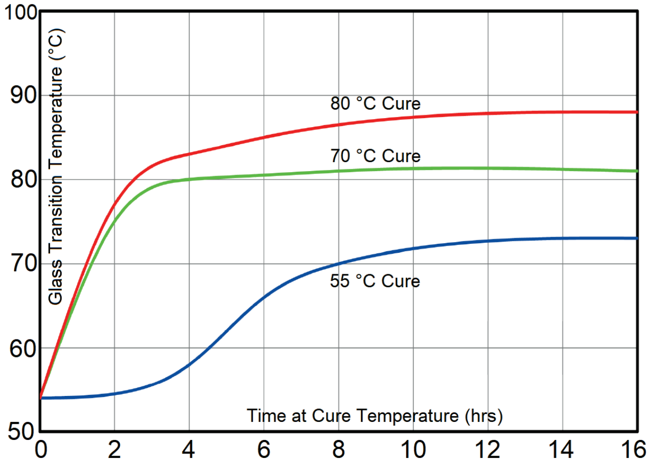

Figure 7 Glass transition temperature vs. cure cycle

With this epoxy resin system, different glass transition temperature can be achieved, depending on the curing conditions of the composite part. Curing the composite sheet at elevated temperature of 80 °C for additional 8 hours, raises the glass transition temperature of the composite sheet to a higher tolerance.

5 TESTING AND TEST RESULTS

From the manufactured carbon fiber sheet, three samples were cut-out with dimensions of 300 mm length, and 25 mm width, presented on Fig. 8. The three coupons are used to test the tensile strength of the manufactured carbon fiber sheet. The test is implemented using the ASTM D3039 standard, using a 250 kN tensile strength tester. The test of the three coupons was conducted in a room temperature environment.

The test sample is mounted on the tensile strength testing machine, using suitable grips, used for holding the specimen, and providing a sufficient and even distribution of pressure to prevent slippage of the specimen during the test. The two grips hold on combined length of 120 mm of the specimen (60 mm on each side), presented on Fig. 9. The displacement between the grips determined by the ASTM D3039 standard is 2 mm/s.

To calculate the tensile strength of the composite samples, Eq. (1) was applied:

$$\sigma_{\max} = \frac{F_{\max}}{A}, \tag{1}$$

where: $\sigma_{\max}$ - ultimate tensile strength (MPa); $F_{\max}$ - maximum load before failure (N); A - average cross section of the coupon (mm^2).

Figure 8 Representation of the test samples before the testing procedure

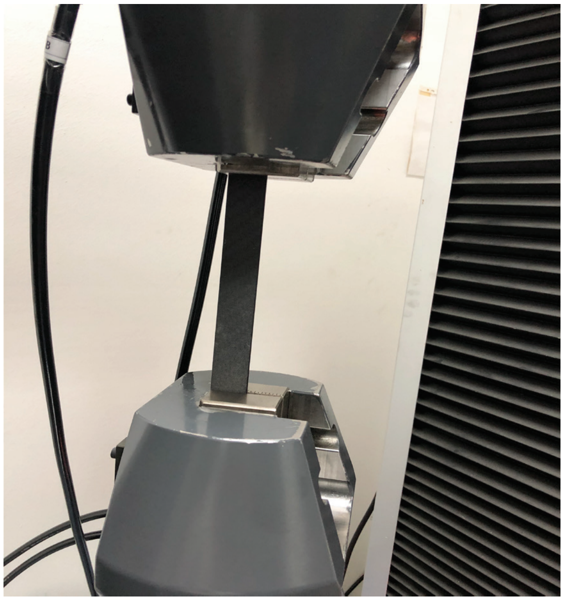

Figure 9 Mounted carbon fiber sample

The results of the ultimate tensile strength of the coupons are shown in Tab. 3.

Table 3 Results from the ultimate tensile test

Test Samples	$\sigma_{\max}$ (MPa)
Sample 1	539,24
Sample 2	512,62
Sample 3	488,58

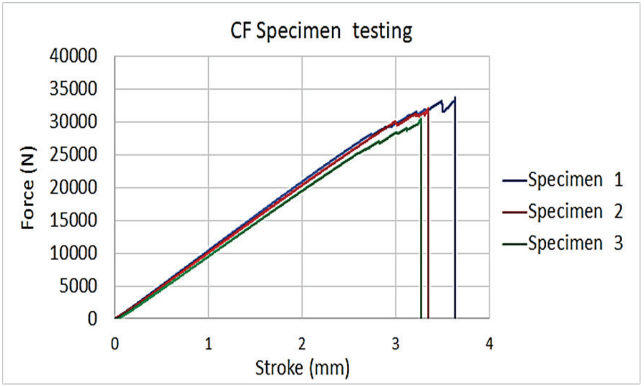

Figure 10 Graphic representation of the conducted tensile test on the three samples

Specimen 1 withstood the highest load of the three coupons, reaching fatal failure at 34.1 kN and extension of 3.6 mm. Specimen 2 withstood maximum load of 32.6 kN and extension of 3.3 mm before fatal failure. Specimen 3 withstood the lowest load of 3.1 kN and extension of 3.2 mm before fatal failure, shown on Fig. 10.

The specimens after testing are presented on Fig. 11. Specimen 2 and 3 have two break points.

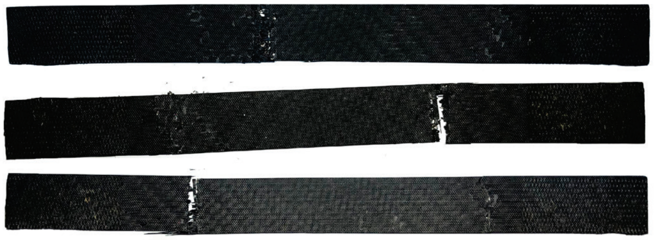

Figure 11 Aftermath of the test samples

6 CONCLUSION

Open moulded hand lay-up process combined with its low cost for tools, provides adequate product, which almost entirely depends on the workers ability. The final result from the manufacturing of the composite sheet, is a product with some surface voids, pinholes and trapped air. The surface of the carbon sheet, due to the nature of the process (lack of vacuum environment) has many voids. To get a surface rid of any imperfections and voids, the sheet needs to undertake additional treatment to get a perfect smooth finish. The final thickness of the manufactured sheet is 2.5 mm. When compared to the thickness of the carbon fiber cloth, which is approximately 1.8 mm, it's concluded that the remaining 0.7 mm is gained from the resin. With this procedure, the final product is resin rich, which in turn gives us a part with an increased mass and lower mechanical properties in contrast to the other carbon fiber manufacturing processes, due to the excess resin.

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