J Inno Sci Eng, 2022, 6(2):248-258
https://doi.org/10.38088/jise.979229

Research Article

Mechanical Properties of Thermoplastic Filament Stitched Carbon Fiber Reinforced Composites

Gokcenur Saglam [1*], **Ayse Celik Bedeloglu** [2]

[1*] *Ermetal Otomotiv ve Eşya San. Tic. A.Ş.*

[2] *Department of Polymer Materials Engineering, Bursa Technical University, 16310 Bursa, Turkey.*

Abstract

In recent years, the use of composites has attracted great interest in both academia and industry, especially due to their lightness and mechanical properties. In this study, acrylonitrile butadiene styrene (ABS), poly(ethylene-co-methacrylic) acid (EMAA) and ethylene vinyl acetate (EVA) filaments were produced in a single screw extruder. The produced filaments were integrated into composite materials by stitching method, and then, the mechanical properties of the filaments and composites were investigated. According to the tensile test results, it is concluded that the stitching process affects the mechanical properties of the composite material.

The strength of the composite material produced with EVA filament with a maximum diameter of 1mm increased by 23%. Apart from these, the composite materials produced with 1mm ABS and 0.6mm and 0.8mm EMAA filaments increased by an average of 15%. There was no significant change in the elongation of the composite material produced with 0.6mm, 0.8mm, and 1mm diameter filaments. The elongation of the composite material produced with only 1mm diameter ABS filament increased by 12%. The elongation values of the composite material prepared with 0.6mm diameter EMAA and EVA polymers decreased also by 15%.

Keywords: 3-Dimensional Reinforcement, Carbon Fibre-Reinforced Polymers (CFRPs), Stitching, Filament, Fibre-Reinforced Polymer Composites (FRPCs).

Cite this paper as:
Saglam, G., Celik Bedeloglu, A. (2022). *Mechanical Properties of Thermoplastic Filament Stitched Carbon Fibre Reinforced Composites* .Journal of Innovative Science and Engineering. 6(2): 248-258

*Corresponding author: Gokcenur Saglam
E-mail: gkc.nur_saglam@hotmail.com

Received Date: 05/08/2021
Accepted Date: 06/12/2022

1. Introduction

Fibre-reinforced polymer composites (FRPCs) are preferable in many areas due to their promising mechanical properties, such as high specific strength, high specific modulus, good fatigue resistance, high damage tolerance, and excellent processability [1–3]. For example, using carbon fibre-reinforced polymers (CFRPs), instead of metal in automotive, can result in a weight reduction of up to 15%. This feature has been proven to improve the fuel efficiency of vehicles [4]. FRPCs are mostly formed by overlapping fibre reinforcements or prepreg layers under the heat and pressure to form a complex three-dimensional network structure [5]. In addition, thermoplastic additives, such as particles, filaments, nanoflakes or nanotubes affecting the material properties, can be applied with different techniques to obtain improved properties in the composite materials [6].

The through-the-thickness stitching method with filament increases high in-plane strength, interlaminar fracture toughness, impact damage tolerance, [7] and tensile strength of composite materials [8–10]. It also has a higher resistance to delamination cracking under low energy, high energy, dynamic loading, and ballistic effects [11,12]. However, they suffer from damage by delamination cracking when the stitching needle passes through the prepreg tape or fabric, a gap is formed in the area, and the fibres are separated from each other. The type and structure of the stitch are the most important parameters affecting the composite performance. Four different types of stitches are applied: lock stitch, modified lock stitch, chain stitch, and double lock stitch [13,14]. While conventional lock stitches are used in the fabric industry, other stitch types are frequently used in the composite industry [13].

To develop stitched composites, the poly(ethylene-co-methacrylic) acid (EMAA) and ethylene vinyl acetate (EVA) and acrylonitrile butadiene styrene (ABS) polymers can be chosen because of their properties. EMAA is a hard, light, easily workable, thermoplastic polymer without the need for plasticizers. It also has applications in composite materials due to its low melting point, toughness, and high melt flow index. The most important feature is that it is an effective agent because it contains functional groups that are chemically reactive with the amine groups in the epoxy [15–22].

EVA is a transparent, high mechanical strength, flexible, rubbery thermoplastic copolymer. In addition, its structure consists of varying amounts of vinyl acetate (VA) and ethylene. Its crystallinity, melting point, and hardness depend on the VA content in its structure. Generally, the VA rate varies between 1-40%. As the VA content increases, its crystallinity decreases, so the melting temperature (Tm) decreases. It becomes softer and more elastic. Impact resistance and tear resistance increase. The glass transition temperature (Tg) in EVA is not affected by the VA ratio and is between (-35) and (-25). The EVA is a well-known adhesive and has a very low viscosity [23,24].

ABS is an opaque, amorphous polymer. It is one of the important engineering plastics consisting of the polymerization of styrene, acrylonitrile, and butadiene monomers. Each monomer in its structure has different properties. Acrylonitrile, heat and chemical resistance, long-term thermal stability, and toughness; Butadiene, impact resistance and maintaining its properties at low temperature; Styrene provides hardness, surface gloss, and easy workability [25]. Also, ABS has a pendant functionality from maleic anhydride and cyanate groups which may have been capable of interacting with the epoxy resin with the aromatic pendant group [14,26–28]

According to the literature review, there is no similar study with EVA and ABS filaments. The stitching method with EMAA filaments has been studied, but its mechanical properties has not been studied sufficiently.

Therefore, the aim of this study is to produce filaments with 0.6mm, 0.8mm, and 1mm diameters from EMAA, EVA, and ABS polymers and use them to stitch the prepregs to improve the mechanical properties. In order to measure the mechanical properties, tensile and flexural tests were performed both on the stitched and un-stitched composites.

2. Material and Methods

In this study, EMAA, ABS, and EVA polymers which are suitable for injection method were preferred. The EMAA polymer has a density of 0.94 g/cm^3, MFI value was 395 g/10 min, and trade name Nucrel® 2940 was obtained from DuPont. ABS polymer has a density of 1.02 g/cm^3, MFI has a value of 12g/20min, trade name ABS HI100. EVA polymer, vinyl acetate content has a 19%, has a density of 0.941g/cm^3 and has a MFI value of 2.5 g/10min and trade name Greenfleks ML 50 was purchased from RESINEX. The composite materials used in this study were fabricated by unidirectional carbon fibre-epoxy prepreg (VTM 264) was supplied by SPM Prepreg System.

2.1. Preparation of Thermoplastic Filaments

Extrusion Line (Polmak Plastik/Lab Extruder) 18MM device was used for filament production. In this study, the effects of two different parameters on the filaments were investigated as shown in Table 1. In the article, EMAA, EVA, and ABS filaments with diameters of 0.6 mm, 0.8 mm, and 1 mm were produced using the optimum parameters.

Table 1. Extrusion parameters of filaments

Filament Code	Extrusion rate (r/min)	Extrusion traction rate (r/min)
ABS06	2.5	8
ABS08	4	7.5
ABS1	4.5	4.6
EVA06	3.5	10
EVA08	5	7
EVA1	5.5	5.1
EMAA06	3.5	6
EMAA08	5	6.5
EMAA1	7.5	

2.2. Fabrication of Unstitched and Stitched Composites

The carbon fibre/epoxy composite prepreg was stitched manually in the thickness direction with EMAA, ABS, and EVA filaments, respectively. The demonstration of the stitched structure is shown in Fig.1. In the process, the stitch density was 1.0 stitch/cm^2. The unstitched and stitched composites were hot press cured at 120°C under 0.05 MPa. Subsequently, all composite materials were post-cured in an air-circulated oven for 40 minutes at 150°C under 0.05 MPa [29]. In the stitching process, the process was easier as the EMAA and EVA filaments are very flexible and was more difficult because the ABS filament is hard.

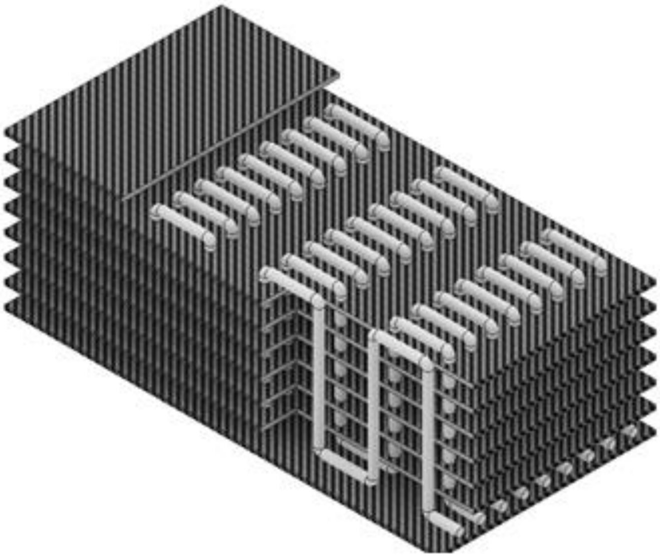


Figure 1. The demonstration of the stitches in the carbon fibre–epoxy composite

2.3. Characterization

The tensile strength, elastic modulus, yield strength and tensile strength tests of the filaments were performed with reference to ASTM D3822/D3822M-14 standard. The length of the filaments prepared in accordance with the standard is 150mm [30] .

In order to measure the tensile strength and tensile modulus of elasticity of the composite materials, tensile tests were carried out according to the ASTM D 3039/D 3039M-00 standard. Composite materials were prepared as 25mm in width, 250 mm in length, and 2.5mm in thickness in accordance with the standard [31]. For each composite type, at least five samples were tested. Tensile tests of composite materials were carried out in accordance with the standards at 2 mm/min [30,31].

The flexural strength of the composites produced were tested in accordance with ASTM D 7264/D 7264M-07 standard. The width of the samples prepared in accordance with the ASTM D 7264/D 7264M-07 standard was 13 mm, and the thickness/gap ratio was taken as 1/32 [32].

3. Results and Discussion

3.1. Tensile Test Results of Filaments

As seen in table 2, the tensile stress of the 0.6 mm diameter EMAA filament is 25.21 MPa. The strength of the 0.8mm and 1.0mm diameter filaments decreased by 4% and 2%, respectively. Test results showed that filament diameters did not have a serious effect on strength [33].

The tensile strength of the 0.6 mm diameter EVA filament is 33.73 MPa. According to the test results, it was observed that as the diameter of the filaments increased, the strength increased by more than 30%.

The tensile strength of the 0.6 mm diameter ABS filament is 19.84 MPa. The strength of 0.8mm and 1.0mm diameter filaments increased by 70%. According to the results, there was a significant increase in mechanical values as the diameter increased for ABS [34,35].

Table 2. Stress-strain values obtained as a result of tensile tests of filaments

Material type	Filament diameters	Stress (MPa)	Standard deviation	Strain (%)	Standard deviation
EMAA	0.6	25.51	0.84	139.36	3.96
	0.8	24.23	0.39	329.4	14.16
	1	22.66	0.18	200.39	4.55
EVA	0.6	33.73	1.44	163.03	27.32
	0.8	21.05	1.28	146.96	17.29
	1	24.07	0.43	408.22	33.08
ABS	0.6	19.84	4.21	16.93	2.32
	0.8	33.59	0.46	47.35	23.12
	1	33.97	0.33	16.45	2.05

3.2. Tensile Test Results of Composites

As seen in Fig. 3, the tensile strength of the unstitched composite is 368 MPa. The strength of the stitched composite material prepared with 1 mm diameter ABS filament increased by 14%. The strength of composite materials produced with 0.6 mm and 0.8 mm diameter filaments decreased by 41% and 36%, respectively. When the chemical structure of ABS is examined, it contains unsaturated hydrocarbon and nitrile groups that react with epoxy groups. ABS has a high melting point. In this study, the process temperature was approximately 150°C, and ABS could not completely melt in the composite material, and it could not spread between the layers because its viscosity was too dense. For this reason, although ABS has functional groups that will react with the epoxy matrix, it has not been found to have an effect on the tensile strength since it cannot come into contact with the sufficient surface [36,37]. As a result, its strength decreased.

As shown in Fig. 2 , the strength of the stitched composite material produced with EMAA filament with 0.6 mm and 0.8 mm diameters increased by 16% and 7%, respectively. The strength of the composite material produced with the filament used with a diameter of 1mm decreased by 6%. The test results reveal that the filament diameter did not have a great effect on the tensile strength. EMAA contains functional groups that are chemically reactive with amine groups in epoxy. As a result of the reaction, water is released, and the resulting water creates vapor pressure in the temperature environment. With this high pressure, EMAA spreads easily between the layers. As the diffusion of EMAA between layers increased, its chemical reaction amount with the epoxy matrix increased. [17,38,39]. Therefore, there was no significant change in the strength properties depending on the filament diameter.

The strength of stitched composite materials produced with 1 mm diameter EVA filaments increased by 23%, as shown in Fig. 2. The strength of composite materials produced with EVA filaments used in 0.6mm and 0.8mm diameters decreased by 7% and 16%, respectively. The composite manufacturing process temperature is above the EVA melting temperature. EVA has a very low viscosity compared to EMAA and ABS and shows adhesive feature [40–42]. Therefore, the 1 mm diameter filament caused an increase in strength in the stitched composite.

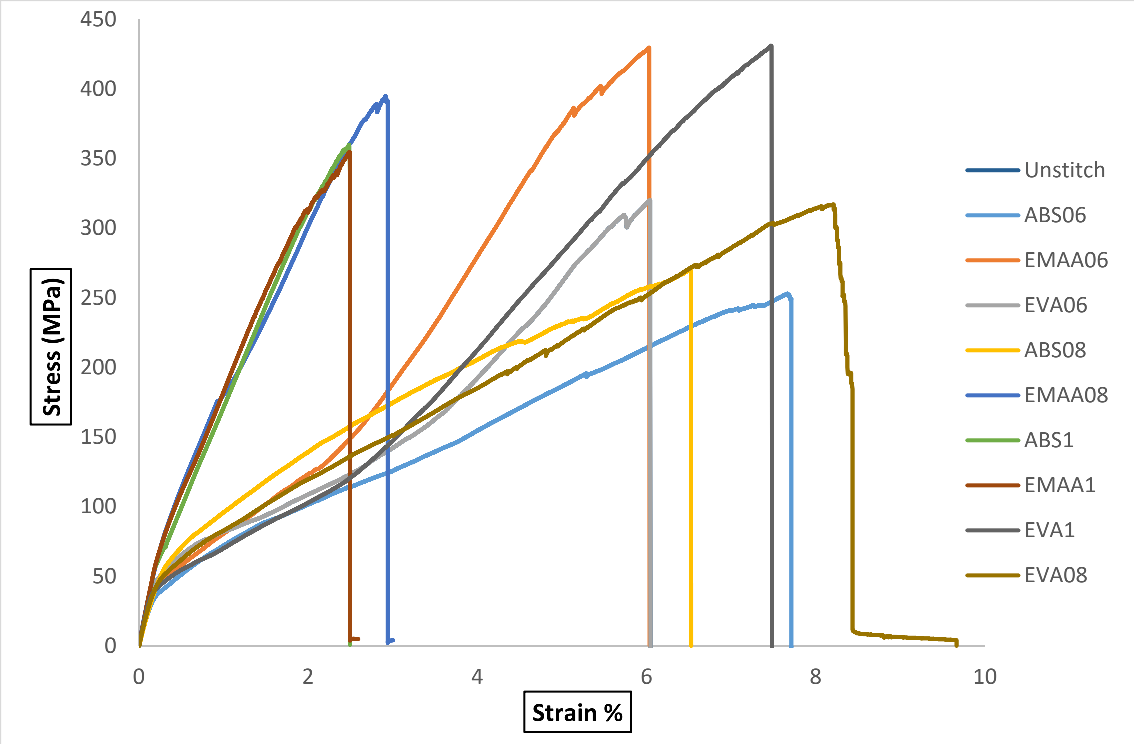


Figure 2. Stress-strain curves of composite materials produced with different filament diameters

3.3. Flexural Test Results of Composites

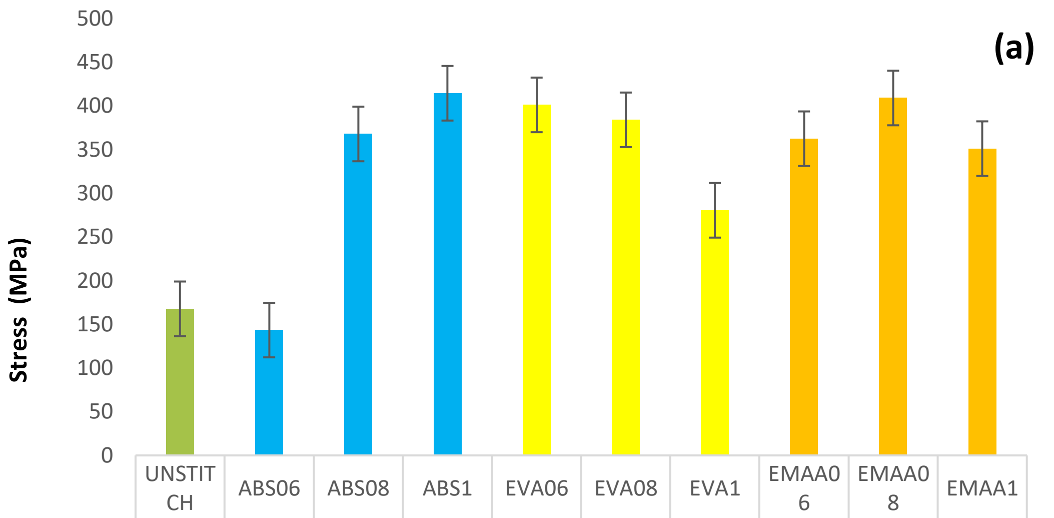
A three-point bending test was performed according to ASTM D 7264/D 7264M-07 test standards on both stitched and unstitched composites produced with filaments using different types and diameters. In this test, the specimen is in a support opening, and the load is applied to the midpoint by the loading nose [43].

As seen in Fig. 3, the flexural strength of the unstitched composite is 167.81 MPa. As shown in Fig. 3, the strength of the stitched composite material produced with ABS filament with a diameter of 0.8mm and 1mm increased by 119% and 147%, respectively, while the strength of the composite produced with a diameter of 0.6mm diameter decreased by 15%. No significant change was observed in the elongation of composite materials produced with filaments of 0.6mm and 0.8mm diameters. However, the elongation of the composite material produced with a 1mm diameter filament rose 12%, and the material became more ductile.

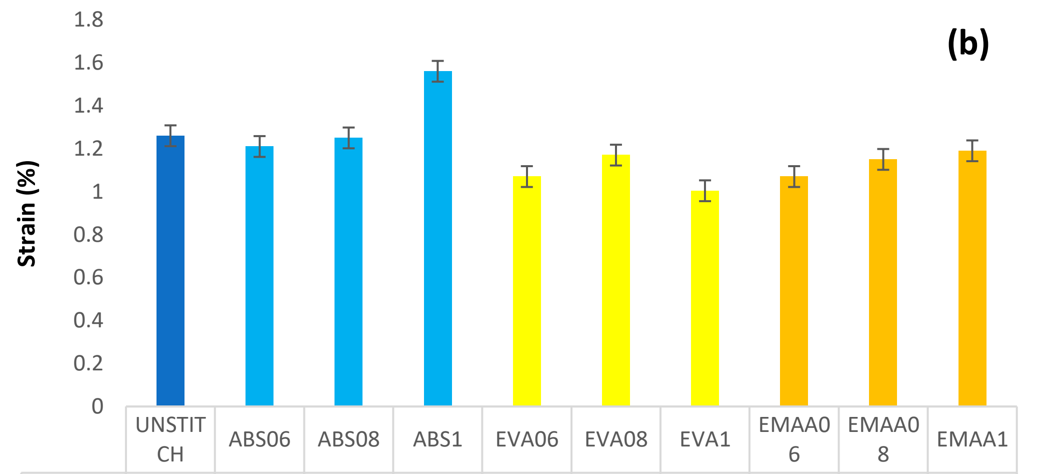
As shown in Fig. 3., the strength of the stitched composite material produced with EVA filament with a diameter of 0.6mm, 0.8mm, and 1mm increased by 140%, 129%, and 67%, respectively, No significant change was observed in the elongation of all composite materials. Only, elongation of the composite material produced with 0.6mm and 1mm diameter filament decreased 15% and 20%, respectively, and a more brittle structure was formed in the materials.

According to the results of the composite material prepared with EMAA filament, the strength of the composite material produced with 0.6 mm, 0.8 mm, and 1 mm diameter EMAA filament increased by 116%, 145%, and 109%, respectively. According to the elongation result, there was a 35% reduction in the elongation rate of the composite material produced with only 0.6mm diameter filament, and the material reached a more brittle structure. There was no significant change in the elongation of the composite material produced with 0.8mm and 1mm diameter filaments.

When the flexural and tensile test results are examined, it has been proven that all results are in parallel with the results of the tensile test of the filaments.



	UNSTITCH	ABS06	ABS08	ABS1	EVA06	EVA08	EVA1	EMAA06	EMAA08	EMAA1
Series1	167.81	143.47	367.95	414.588	401.232	384.13	280.562	362.52	409.12	351.15



	UNSTITCH	ABS06	ABS08	ABS1	EVA06	EVA08	EVA1	EMAA06	EMAA08	EMAA1
Series1	1.26	1.21	1.25	1.56	1.07	1.17	1.004	1.07	1.15	1.19

Figure 3. The variation of the stress(a) strain(b) graphs obtained as a result of the three-point bending test of the composite materials prepared with ABS, EMAA, and EVA filaments according to the filament diameter

4. Conclusion

In this paper, the effects of using EMAA, EVA, and ABS filaments in the composite materials with stitching process on the some mechanical properties of composites were presented. It has been proven that filaments of different types and diameters greatly affect the mechanical properties of the stitched composites. According to the test results, it has been concluded that the stitching process reduces the mechanical properties of the composite material. The strength of the stitched composite material produced with 1 mm diameter EVA filament increased by 23%. Apart from these, an average of 15% increase in tensile strength was achieved in stitched composite materials produced with 1mm ABS, 0.6mm and 0.8mm EMAA filaments. During the stitching process of the filament, the separation of the fibres from each other, the formation of resin-rich regions, porosity, fibre breakage, and the formation of cracks between the resin may have caused these results [10,44,45]; the decrease in the tensile strength of the composites. According to the 3-point bending test results, it has been found out that the stitching process increased the flexural mechanical properties of the composite material. There was no significant change in the elongation of the composite material produced with different type and diameter of filaments. The elongation of the composite material produced with only 1mm diameter ABS filament increased by 12%. The elongation values of the composite material prepared with 0.6mm diameter EMAA and EVA polymers also decreased by 15%.

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