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Investigation of Thermal and Mechanical Properties of Aramid Fiber Reinforced Thermoplastic Polyurethane Elastomer Composites

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Abstract: Along with the emergence of thermoplastic polyurethane materials with its elastomeric behavior, there has been an improvement in the production of composites with functional properties by adding additives as well as advantages such as high production rates and diversity. In this study, thermal and mechanical behaviors of thermoplastic polyurethane (TPU) elastomer reinforced with aramid fiber (Kevlar) fabrics with different layers were investigated. Particular emphasis has been placed on the optimization of parameters such as good distribution and impregnation of TPU elastomers used as reinforcements on Kevlar interfaces. Composite samples prepared in 1, 2 and 3 layers of Kevlar fabric by using hot pressing method which were heated at 180 °C under the pressure of 10 MPa for 20 minutes to obtain the final product. Optical, modulus of elasticity, tensile strength, % elongation and thermal conductivity values of TPU reinforced Kevlar composite materials with different layer ranges are compared. It is concluded that the high mechanical strength and the high thermal conductivity values are associated with the amount of thermoplastic polyurethane materials between the kevlar sheets in few layered composite structures. It is also seen that the mechanical strength strongly depends on pore volume, adhesion on fiber-matrix interfaces and matrix concentration on aramid fiber reinforced thermoplastic polyurethane composites.

Aramid Lif Takviyeli Termoplastik Poliüretan Elastomer Kompozitlerin Termal ve Mekaniksel Özelliklerinin İncelenmesi

Anahtar Kelimeler
Aramid fiber,
Termoplastik elastomer,
Termal iletkenlik,
Mekanik dayanım

Özet: Elastomerik davranış gösteren termoplasik poliüretan malzemelerin çıkışı ile birlikte yüksek üretim oranlarına ve çeşitliliği gibi avantajların yanı sıra katkı maddelerinin ilavesi ile fonksiyonel özelliklere sahip kompozit üretiminin de önünü açan bir gelişme olmuştur. Bu çalışmada, farklı katmanlara sahip aramid fiber (Kevlar) kumaşlar arasına emdirilmiş termoplastik poliüretan (TPU) elastomer kompozit yapıların termal ve mekaniksel davranışları incelenmiştir. Takviye elemanı olarak kullanılan TPU elastomerlerin Kevlar yüzeylerine iyi dağılımı ve emdirilmesi gibi parametrelerin optimizasyonuna özel önem verilmiştir. Sıcak presleme yöntemi ile 1, 2 ve 3 katmanlı olarak hazırlanan kompozit numuneler 180 °C sıcaklık, 10 MPa basınç altında 20 dakika bekletilerek nihai ürün elde edilmiştir. Farklı katman aralıklarına sahip TPU takviyeli Kevlar kompozit malzemelerin optik, elastisite modülü, çekme dayanımı, % uzama ve termal iletkenlik değerleri karşılaştırılmıştır. Az katmanlı kompozit yapılarda mekaniksel dayanımının yüksek olmasının yanında termal iletkenlik değerlerinin yüksek olması termoplastik poliüretan malzemelerin kevlar tabakalar arasındaki miktarı ile ilişkili olduğu sonucuna ulaşılmıştır. Ayrıca, aramid lif takviyeli termoplastik elastomer kompozitlerin mekanik mukavemetin gözenek hacmine, fiber-matris ara yüzeylerin yapışmasına ve matris yoğunluğuna bağlı olduğu görülmektedir.

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1. Introduction

A composite material is a group of materials that coming together at least two different materials such as metal, ceramic or polymer. The use of composite materials is aimed at producing a new material having superior properties, especially those of the different components having the desired material properties. Therefore, composite materials are widely used in the automotive sector as well as in many other industrial fields [1].

Nowadays, aramid fibers have been widely used as reinforcing agents for high mechanical strengths and impact resistances. It is also known that aramid fibers used as reinforcing agent not only on thermoset polymers but also on thermoplastic polymer matrices so far. Due to the brittle behavior of thermoset polymer based Kevlar composites [2-4], its usage area and production performance are very restricted. On the other hand, fiber reinforced thermoplastic composites possess several advantages in terms of recyclability, cost effectiveness and flexibility of design. Main advantages of thermoplastic elastomer are the fact that they can be processed several times, exhibited high stiffness, excellent resistance to abrasion, high toughness and load-bearing capacity.

Impregnation of fibers into thermoplastic polymer elastomer is very critical. To obtain an excellent reinforcing properties of Kevlar among thermoplastic polymer resin, interlaminar adhesion combines strong fiber-matrix interfacial adhesion to minimize compressive breakdown [5].

Many researchers focused on improving interfacial adhesion between aramid fibers and thermoplastic polymers. Commercial coupling agents, chemical modifications, bromine or chloride treatment were applied for this purpose [6]. Another approach for improving its modulus and yield strength is that tuning fiber direction in matrix and determination of the fiber volume fraction in composite [7]. By using thermoforming process, fiberglass plain weft-knitted fabric with thermoplastic elastomers shows high stretchability which strongly depends on knitting density and product thickness distribution [8, 9]. Aramid, glass, cotton and carbon fibers as reinforcement fibers and poly(ethylene-terephtalate) (PET), poly (ether-ether-ketone) (PEEK), poly (phenylene sulphide) (PPS), polypropylene (PP), polybenzoxazine (PBA), polyolefin, polyurethane as matrix are mainly considered in polymer composites as well [10-15].

For investigating fiber reinforced thermoplastic elastomer composites, Tausif et al. focused on the role of aramid fibre dimension and degree of fibre entanglement on prepared composite. Depending on the fibre type, PET and lyocell have the potential to increase the tensile modulus of compression molded TPU composites when introduced as nonwoven preforms with solid volume fractions of <10% [16]. Jiango et al. also investigated Kevlar reinforced TPU elastomers by using thermoforming. Since Kevlar based composite materials are examined on its impact and ballistic properties, they evaluated the notch sensitivity and tear resistance of the final product and found that notch sensitivity and stress concentration in notched specimen is strongly depends on Kevlar fibres not on TPU matrix structure [17].

In this work, our approach is to incorporate kevlar fabric layers with thermoplastic polyurethane elastomer composites by using hot pressing technique [18]. This technique provide strong adhesion and uniform distribution on aramid fiber reinforced TPU elastomer composites. Mechanical and thermal properties of various layer of samples were investigated and compared.

2. Material and Method

Commercial (Lubrizol) TPU elastomer of the Pellethane series 2363-80A (density: 1.13 gr/cm^3) was obtained from Dow Chemicals [19] as matrix and it was used as received. Fiber reinforcement material was selected as plain aramid fiber fabric (Kevlar-49) 1100 dtex in warp (10.5 threads/cm), weft (10.5 threads/cm) and total weight of fabric is about 207 g/m^2 provided from Dupont Turkey. Furthermore, Kevlar 49 1100 dtex has value of 151,7 GPa longitudinal elasticity modulus, 4,14 GPA transverse elasticity modulus and 0,35 poission's ratio [20]. The volume fraction of aramid fiber fabrics used in all the three sets of prepared composites was maintained at 66% of the composite volume.

Composite material was prepared by hot pressing method. For 1 layered Kevlar fabric reinforced TPU elastomer composite, kevlar fabric was placed between TPU granules and then hot pressed at 180°C for 30 min. under 10 MPa. To achieve better adhesion between fabric and matrix, the temperature and duration is kept high as possible. Afterwards, composite material was allowed to cool down to room temperature. This process is also applied for 2 and 3 kevlar layered TPU elastomer composites. All samples were finally cut to size suitable for inspection of mechanical and thermal properties with the aid of water jet.

Three different ply number of Kevlar reinforced TPU elastomer composites were produced. The respective compositions are indicated in Table 1. Samples were coded according to the stacking sequence of TPU elastomer sheet and Kevlar fabrics. Here, A and B indicate TPU elastomer and Kevlar fabric, respectively.

Table 1. Designation and composition of the materials produced

Classification Number (# of Kevlar Fabric in Composite)	Sample Code
1 layers	ABA
2 layers	ABABA
3 layers	ABABABA

Interfaces of three different layer of Kevlar fabric and TPU elastomer were taken from an Olympus BH2-UMA Optical microscope. It was undertaken to examine the interfaces of kevlar fabrics in the thermoplastic polyurethane elastomer and also investigate the presence of voids and adhesion between layers.

The tensile strength was determined on Zwick/Roell Universal Testing machine with a strain rate of 5mm/s at room temperature. Tensile tests were carried out on the basis of ASTM D-3039 standard. The tensile test of each layered sample was made three times and the average of the results was calculated. The dimensions of the tensile test specimens are 25x165 mm.

The thermal conductivity coefficient measurements were carried out in accordance with the Fox-50 IAO and EN 12664-12667 standard. Measurements were made for nine different temperatures starting from 0 °C to + 80 °C in increments of 10 °C.

3. Results

In line with aims of the study, this section consists of optical, mechanical and thermal evaluation of aramid fiber reinforced TPU elastomer composites.

Figure 1 shows optical micrographs of three types of Kevlar reinforced composite interface. For samples containing 3 layers of Kevlar the presence of void is relatively higher than other two composites because of high viscosity during hot pressing which made air elimination more difficult and resulted in extensive voids (circled area) presence as seen in Figure 1b and 1c.

When specimens with different layers were observed after the tensile test, it is clearly seen (Figure 2) that

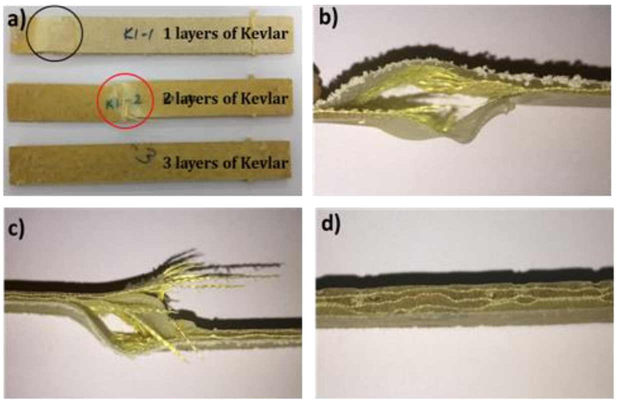

Figure 2. Photograph of fractured samples including (a) Top view of tensile test samples, (b) Cross section of 1 layers of Kevlar (black circled area at Fig. 2a), c) Cross section of 2 layers of Kevlar (red circled area at Fig. 2a), d) Cross section of 3 layers of Kevlar

the outer fracture appeared in 1 and 2 layers of Kevlar composite, while inner fracture appeared in 3 layers of Kevlar composite. It has been observed that composites having a low matrix concentration cannot prevent the fibers from breaking during tensile test. In addition, early breakage of the 3-layer composite material is a due to high intrinsic porosity.

In the current study, the composite strength was strongly related to pore volume and adhesion on fiber/matrix interfaces and matrix concentration. For 1 layers of Kevlar composite shows a sudden drop at 70.1 MPa, which is related to fiber breakage (Figure 3). A sudden drop in strength occurs with the fiber break, but the complete break occurs after a long time because the matrix exhibits elastomeric behavior in the composites. A poor adhesion of the matrix to fiber surfaces may cause breakage [21]. At constant time, temperature and pressure applied on all composites, 3 layers of Kevlar composite shows high pore volume at inner and outer surfaces, which reduces its modulus of elasticity. Since the heat transfer rate between the layers of kevlar under hot press is low, the thermoplastic polyurethanes as granules do not adhere fully to the fiber surfaces and cause the formation of a porous structure [22]. Therefore, the pore volume of 3 layered Kevlar composite is relatively higher than other two composites.

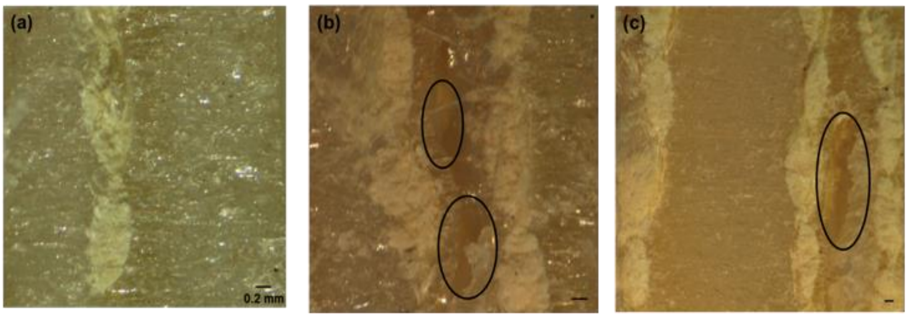

Figure 1. Optical image of thermoplastic polyurethane elastomer composite containing (a) 1 layers of Kevlar, (b) 2 layers of Kevlar and (c) 3 layers of Kevlar showing their macroporosity (circled area). Scale bar is set as 0.2mm for all samples.

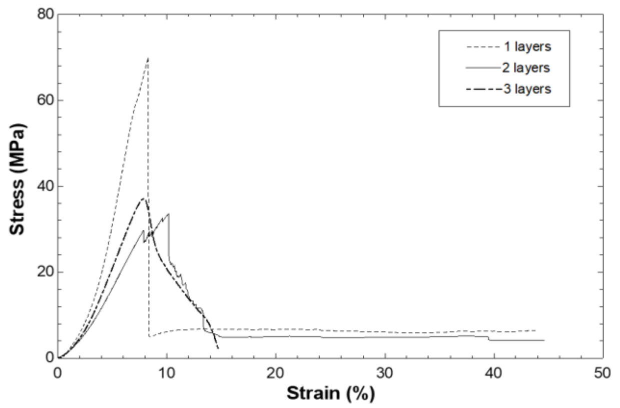

Figure 3. Engineering stress – strain curve of 3 different ply number of Kevlar reinforced TPU composites

In Table 2, it affirms the above observation in terms of their value of modulus of elasticity, ultimate tensile strength and elongation at break. It is also interesting to observe that modulus elasticity and tensile strength values of 2 layers and 3-layers of Kevlar composites are close to each other while it is expected to see high values for 3-layers Kevlar composites. Due to high porosity volume exist on 3 layers of Kevlar composite, it decreases its elasticity modulus close to 2 layers of Kevlar composites.

As it is known from previous studies [18], the fiber properties in machine direction (MD) and matrix properties in cross direction (CD) is suppressed. To observe the mechanical property of polymer composites, it is expected that the tensile strength value in MD direction is high if the fiber strength is considered to be larger than the matrix strength. In this study, the effect of the number of fiber fabrics on the mechanical properties is investigated, thereby no need to consider the tensile strength in the CD.

Table 2. Mechanical properties of 3 different layered final composite

Sample	E (MPa)	σ (MPa)	ε (%)
1 layers	21,6	70,1	43,8
2 layers	117	33,7	44,6
3 layers	113	37,1	14,8

Thermal properties of final material is categorized as its layer of Kevlar fabric. The change in the thermal conductivity coefficients depending on the temperature was investigated in Figure 4. It is clearly seen that the thermal conductivity value increases with increasing working temperature of composite plate samples. This is due to the increase in temperature and the increase in vibration at the molecular level. Increasing vibration directly affects the heat transfer mechanism with transmission and causes the coefficient of thermal conductivity to increase with temperature.

The increase in density for aramid fiber reinforced TPU composite plate caused the thermal conductivity value to increase. The increase in density reduces the amount of porosity in the material. This shortens the

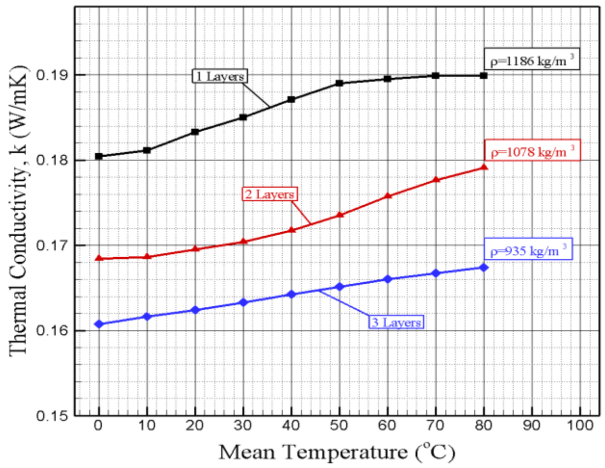

Figure 4. Thermal conductivity coefficients of 3 different ply number of Kevlar reinforced TPU composites with different density values depending on temperature

heat transfer path, which leads to an increase in the coefficient of thermal conductivity. Figure 5 shows the variation in thermal conductivity coefficient as a function of temperature and density. The thermal conductivity coefficient increased with increasing temperature and density.

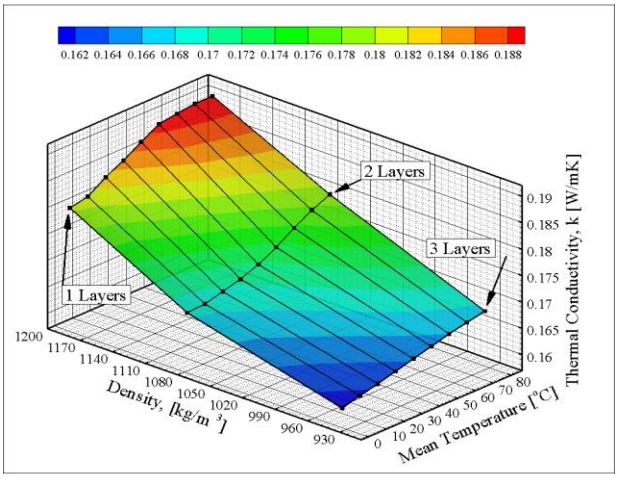

Figure 5. Relation between temperature, density and thermal conductivity of various layered Aramid fiber reinforced TPU composites

Along with increasing number of Kevlar layers, high pore volume is observed and inhibits the increase in mechanical properties. In addition, it has also been understood that the increase in the amount of TPU, depending on the number of layers increased, gives the resulting composite material an insulating property.

4. Discussion and Conclusion

The mechanical and thermal properties of aramid fiber fabric reinforced thermoplastic polyurethane composite were evaluated and the key findings can be summarized as follows:

- 3-layers Kevlar reinforced TPU composite shows high pore volume than other two composites since densification is hindered by aramid fibers and resulted in high porosity structure.

- Mechanical properties strongly rely on adhesion on fiber/matrix interfaces, pore volumes and matrix concentration in the composite structures.
- High mechanical strength and high thermal conductivity values are related with the amount of TPU elastomers between the kevlar layers in low-ply composite structures.
- Increase in the amount of TPU results in a Kevlar reinforced composite an insulating property.

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