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Review of Thermoplastic Composites in Aerospace Industry

Review Article

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Abstract

The use of thermoplastic composite materials in the aerospace industry has been increased substantially in recent years. Main reasons are their advantages such as recyclability, fast production rate, high resistance to chemical and physical damages, and long storage life etc. As a lightweight structure material thermoplastic composites have started use in many aerospace applications. In addition, various research and development (R&D) activities have been performed to spread its usage and increase its potential in the aerospace industry. In this study, thermoplastic composites in general and their applications in the aerospace industry were investigated.

keywords: Aerospace industry; Thermoplastic composites; Carbon fiber; PPS; PEKK; PEEK; PAEK

Introduction

Nowadays, customers request very strict requirements for their products. For example, new material combinations with some properties that traditional materials such as metal alloys cannot meet on their own. In order to meet these demands of large-scale fields such as aerospace, construction, automotive, maritime, wind energy, and defense industry materials have been developed recently. As a result of research and development projects, many markets have been emerged. Composites have gained an important place in these markets. Composites are materials formed by the combination of two or more constituents with different physical or chemical properties in macro dimensions. The components that make up the composite material mostly maintain their chemical, physical, and mechanical properties [1]. Purpose of the composite production is to add new properties to the materials that cannot be fulfill alone. These materials cannot be dissolved in each other. Composite materials consist of three separate components. These are matrix, reinforcement, and interface. The interface is the area between the matrix and the reinforcement that provides contact. The matrix can be made of plastic, metal, and ceramic materials. It keeps the fiber structures together by preventing the reinforcement elements from moving independently within the composite structure and transferring the loads to the reinforcement elements. It wraps the reinforcement elements and gives the composite material its shape [2]. The hardness of composite materials depends on several factors such as fiber placement orientation and type, fiber fraction percentage, base resin hardness, and bond between fibers and base material. Along with the thermosets, thermoplastic composites (TPC) are one of the polymer matrix composites. These days the usage of TPC begin to increase and their position in high-engineering industrial applications such as aerospace and automotive is noticeable as a result of their enormous properties and advantages over thermoset composites.

Overall Properties of Thermoplastics

Thermoplastics can be examined in two parts as structurally amorphous and semi-crystalline thermoplastics. While the amorphous structure provides elasticity, the crystal structure provides strength and rigidity. Thermoplastics are materials that are solid at room temperature. At high temperatures, they begin to soften and become molten. Melted thermoplastics are very easy to shape. Since they become soft and melt when heated, they can be easily shaped. In the examination of the inner chain structures, it has been observed that thermoplastics have chains that are connected to each other by Van der Waals bonds, which are not very strong. Thermoplastics do not have a very rigid structure, so when heated, their viscosity decreases, atomic chains break apart and cause fluidity. When cooled, the broken chains solidify again, allowing the material to become solid.

Due to these properties, thermoplastics can be reshaped and recycled by repeatedly heating and cooling. These features are their biggest advantages over thermosets. There are many forming methods for thermoplastics; extrusion, injection molding, fiber and filament, coating processes, compression and transfer molding, blow molding, rotational molding, thermoforming, casting are one of these methods. The properties of the TPC change according to many effects such as fiber type and reinforcement material, arrangement, length. For instance, hardness of composite materials depends on several factors such as fiber placement orientation and type, fiber fraction percentage, base resin hardness, and bond between fibers and base material. Although the material properties differ according to many factors, some of the general properties can be listed as follows.

- Their hardness and impact resistance are high.
- Depending on the type, they can change shape under pressure even at low temperatures.
- The densities of thermoplastics provide a great advantage in lightness when compared to metals and many other materials.
- The coefficient of thermal expansion is inversely proportional to the bond strength of the material and thus to the melting point of the material. Therefore, thermoplastics, which have weak intermolecular bonds and low melting points compared to metals, have high thermal expansion coefficient.
- Corrosion resistance is higher than metals due to their different atomic structures from metals.

Advantages of Thermoplastic Composites

In the aerospace industry, TPC's usage is rising due to their significant advantages. Fuel costs constitute one of the biggest operating costs of aircraft and various studies are carried out to reduce these costs. In addition, reducing the amount of fuel reduces CO2 emissions. Therefore, high strength but lightweight materials have great importance in aviation. In the meantime, for the automotive and aviation industries, high production rates are important. TPC provides several benefits which make them desirable for these industries in recent years. Their time-cost efficient productions and lightness make TPC preferable over traditional materials. In the aspect of chemical structure, thermoplastic resins are different from thermosets, the cross-linking process that occurs after curing reaction for thermosets is not valid for thermoplastics. This means they do not require a curing cycle afterward consolidation like thermosets and no chemical reaction occurs through the application [3]. In composite manufacturing, curing cycles are one of the main reasons behind the higher costs and time losses but due to their structure, thermoplastic resins do not need curing cycles to present chemical reactions and solidifies easily by heat and pressure which makes them cost and time saver. This gives TPCs numerous advantages. The less time lost means more automated production lines can be designed. Especially in the aerospace industry where the production rates are increasing with the growing world transportation which requires fast and easy manageable production TPCs outshines the other materials. Thermoplastics define their signature benefit due to this ability to be produced automatically. Different types of manufacturing methods are applicable for thermoplastic materials which makes them easier and faster to produce and it makes them desirable for many industries. Another advantage of thermoplastics is their product life. Since thermoplastics do not convert their chemistry during the process of applications they do not necessitate to be stored in special conditions like thermosets. In aerospace industry, thermoset based composites require clean room conditions for production. Clean rooms requirements generally make the productions more expensive and slower. However, thermoplastics can be produced easily with no clean room requirements. Along with their nonperishable nature this gives them an advantage in terms of cost savings, since freezers and clean room conditions require energy, time and money. Also, in the environmental inspection even the energy saving gained by the absence of the special storage conditions is important. Their nonperishable nature also cuts off the problems related to shelf life such as wasting of materials due to expiration dates. Another important advantage of thermoplastics is their ability to reform with relevant heat after applications. This opens a new page for thermoplastic materials and makes them recyclable. Nowadays, the importance of recycling is gaining awareness in terms of environment and economy, and in this context, TPC gain importance with their recyclability. They may be reformed for various times. Correspondingly thermoplastics can be welded in which makes the repairing and bonding applications easy and less time consuming [4]. As known, composite materials tend to degrade due to moisture, in the aviation industry this problem comes to the fore especially in the aircraft parts that are exposed to humidity due to weather conditions. But it can be said that thermoplastic materials are in advantage in this field since their water absorption is poor. They show improved mechanical activity in humid surroundings. Moreover, it can be said that virgin thermoplastic resins are tougher materials in comparison to thermoset resins which improves the resistance to impact [5]. Due to their crystalline structure, it can be said that TPCs generally show better resistance to chemical factors [6]. Their corrosion resistance is high. Despite many advantages, TPCs also have some disadvantages. The most important ones are; high costs of raw materials and high temperature and pressure conditions required for applications. The expenses and energy outgoings required to provide high temperature and pressure conditions can also be added to the disadvantages. But with their promising feature of recycling these materials close the disadvantages by using scrap materials.

Applications of Thermoplastic Composites

The frequently used thermoplastics can be classified as in Figure 1, considering the stated features, advantages and disadvantages. As you go up the pyramid, resistance to high temperatures, abrasion, and chemicals increases.

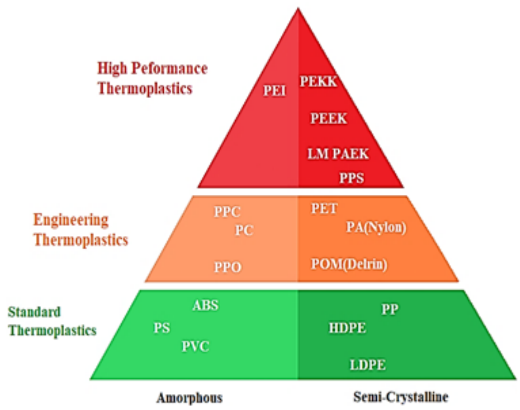

Figure 1: Classification of thermoplastic materials.

In the aerospace industry matrix material of composites such as PEI, PEEK, PEKK, LM PAEK, PPS, and ABS thermoplastics are used commonly which are reinforced with glass fiber (GF) or carbon fiber (CF). In the aerospace industry applications of TPCs have been seen in civil aviation productions, military related defense applications, space and related research studies. Today, it can be said that commercial aviation applications have a large share in the industry and the use of TPCs in aviation is trying to be increased with R&D studies. In one of the market research that carried out in 2019, the thermoplastic composite market in the aerospace and defense industry is forecasted to reach 636.5 M dollars which shows the increasing interest over this material in the industry [7]. Related data is given in Figure 2.

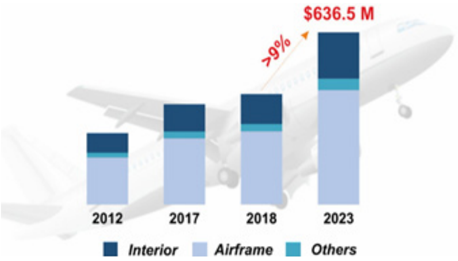

Figure 2: Forecasted aerospace and defense industry thermoplastic composite market growth [7].

Since the aviation industry is increasing rapidly, the demand for production of an aircraft in short periods became an important issue for the industry. Also decreasing the assembly materials such as rivets and fasteners in big structures to make aircrafts lighter is one of the main concerns of today's aerospace companies. Due to their fast production rates, recyclability and welding properties, TPCs are the new research topic for companies to improve the parts made with traditional materials. In context to these reasons most of the aviation companies and institutes released different projects including TPCs as investigation matters. Ever since the 1980s, TPCs in the aerospace industry have been evolving with increasing applications. In Figure 3 some key applications of TPCs in the aerospace and defense industry are given. The development made for Airbus, which is the production of J-nose components from CF-PPS paved the way for TPCs in the commercial aerospace business applications [8].

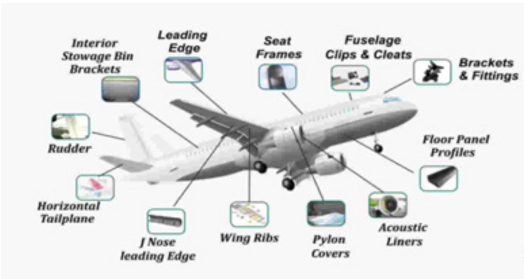

Figure 3: Aerospace and defense industry thermoplastic composite key applications [9].

Thermoplastic composites are used in structural and non-structural parts in the aircrafts. Important applications of TPCs started with ribs and spars of the undercarriage doors following floor panels in the 1990s. As a major consumer Airbus used thermoplastic skins, panels and leading edges in A340-600 and A380 aircrafts. The consumption of TPCs followed by small sized parts such as clips, cleats, brackets and floor panels for commercial aircrafts, jets and military helicopters. By using a rudder and tail made of TPCs, G650 by Gulfstream is one of the important examples. Most commonly used thermoplastic interior parts are pans, backs, trays, and seat frames. For Airbus A330 and A340 sidewall and ceiling attachment rail production is an important example of cabin applications [10]. In Figure 4 some common parts produced by TPCs such as ribs, brackets and stiffeners can be seen.

Following these examples in civil aviation, the use of thermoplastics has gained great momentum, especially with the production methods that developed recently. One of the most important techniques newly used in aerospace is additive manufacturing (AM) or as the more common name 3D printing method. Nowadays, several aerospace companies are testing and using these thermoplastic parts, taking advantage of the fast and precise production features of 3D-printed aircraft parts. One of the examples can be given as the parts produced for 737, 747, 777, and 787 commercial aircrafts of Boeing in which the company profited 3 million dollars just from one of the 787-Dreamliner aircraft series [12]. One of the biggest scales of profit making in this way is the production of parts with difficult geometries error-free and in a short time. Another example that can be given in this context is the aircraft parts of the A350 XWB aircraft of Airbus, one of the largest aviation companies, which were printed using more than one thousand PEI based materials [13]. These parts have paved the way for the use of 3D printing technique in civil aviation, large-scale aircraft and future programs by offering fast, error-free, light, and durable solutions instead of the traditionally used materials and production methods. An example in this context from Turkish Aerospace Industry Inc. can be seen in Figure 5, 3D printed thermoplastic composite ULTEM 1010 based demonstrator and CF-TPC tool for fiber placement process.

Figure 4: Rib, clip, bracket, and stiffener applications of thermoplastic composites in the aerospace industry [11].

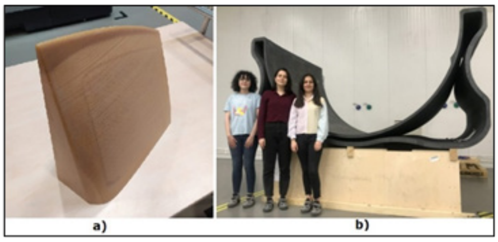

Figure 5: a) PEI based TPC demonstrator b) CF-TPC lay-up tool.

In addition, many ongoing projects aim to carry TPCs into space by using these technologies. Numerous aerospace companies manufacture small and large rocket parts using different production methods of thermoplastics. In this perspective, the German Aerospace Center carried out a study in which one of the main aluminum metal-based structures was replaced with in-situ manufactured CF-PEEK composite and used in the sounding rocket, which is a test part, within the scope of the ATEK project [14]. Within this project reusable and recyclable spacecraft parts are designed and aimed to reduce production costs. The related study can be seen in Figure 6. In addition, weldability, which is one of the biggest advantages of thermoplastics, is one of the essential reasons for the increasing share of TPCs in aerospace applications. Parts produced separately by welding can be made into a single part without any requirements of additional assembly materials. Thus, extra weights caused by mounting materials or damage done throughout the assembly of the materials are prevented. In one of the studies, for Airbus A 330-200 CF-PPS thermoplastic composite demonstrator for leading edge is produced by induction welding [15].

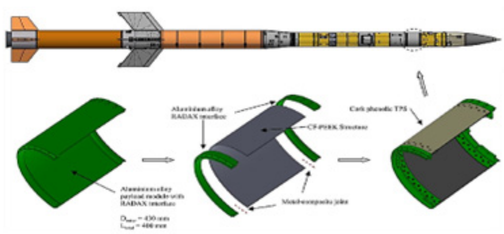

Figure 6: Rocket used in ATEK program and old aluminum part with replaced CF-PEEK thermoplastic composite [14].

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Airbus released the Wing of Tomorrow (WOT) project in 2015 in cooperation with different aerospace companies aiming to develop new methods of productions, usage of newer materials to construct aircraft wings which are cost effective. Within the scope of the WOT project, GKN Aerospace has made a wing rib produced by thermoplastic composite at a level that can race with its aluminum or thermoset composite counterparts. By application of thermoplastic composite decrease in weight, higher resistances of corrosion values are achieved [16]. Figure 7 shows the thermoplastic composite wing produced by GKN Aerospace in terms of the WOT project.

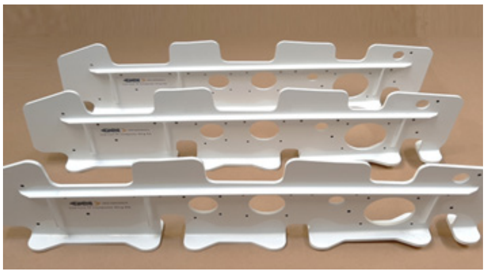

Figure 7: Thermoplastic composite rib by GKN Aerospace [16].

Many programs on the use and development of TPCs in the aerospace industry in Europe have been implemented in partnership with aviation companies and institutions from different countries. Another important project series for the development of thermoplastic aircraft parts is The Thermoplastic Affordable Primary Aircraft Structure Consortium (TAPAS) where it is divided as TAPAS 1 and TAPAS 2. Netherland based projects were first introduced in 2009 which continued to 2017 within cooperation of different aviation companies and institutes. In terms of these projects in which aim to develop new thermoplastic composite components, for TAPAS 1 project demonstrator parts, fuselage, and torsion box from TPCs was produced meanwhile for the TAPAS 2, torsion box and a new fuselage technology was developed [17]. Now these projects are coordinated under the Clean Sky program to improve solutions and increase the number of partners. Clean Sky which was between 2008 and 2016 and Clean Sky 2 which was between 2017 and 2021 are the programs under the European Commission Horizon 2020 project. Within the context of Clean Sky 2 the most important development is the multifunctional fuselage demonstrator which will be produced by thermoplastic composite to reduce the cost and weights. This part is aimed to use in cabin systems [18]. Planned fuselage can be seen in Figure 8.

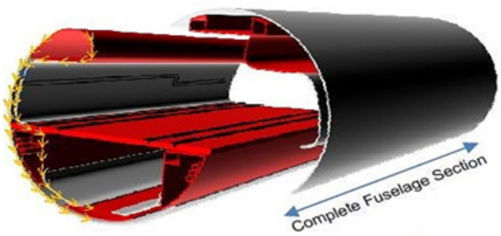

Figure 8: Thermoplastic composite fuselage section [18].

When the experiments and studies conducted in the past and currently being conducted for the aviation industry are examined, PEEK, PEKK, and LM PAEK, which are the most frequently used and most suitable PAEK family members, are evaluated. Taking as an example the applications developed by Airbus as part of TAPAS 2, GKN Fokker recently introduced, which uses what it calls "butt-jointed orthogrid technology" that enables cost effective production of thermoplastic composite body design. The developed a fuselage demonstrator made of thermoplastic as shown in Figure 9.

Another important application by the same company is the use of in-line ultrasonic spot welding at laboratory scale to attach shown in Figure 10 demonstrator's CF/PEEK hinges, CF/PEKK clips and CF/PEEK C-frames produced as part of the Clean Sky Eco-Design project [19]. This study shows that different types of materials can be determined according to the requirements and used on the same product.

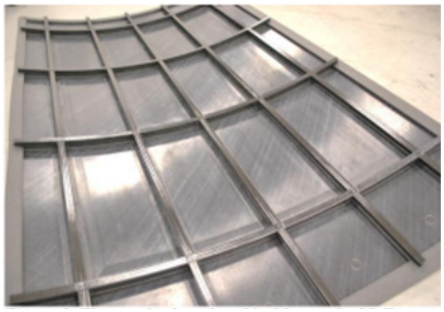

Figure 9: First CF/PEKK orthogrid fuselage panel made in 2013 [19].

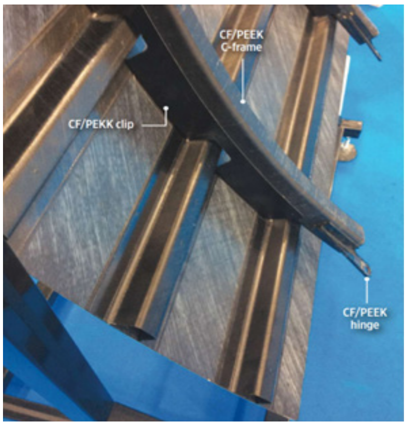

Figure 10: Clean Sky Eco-Design demonstrator [20].

PEKK is a suitable material not only for aerospace applications, but also for space applications, and its future use is expected to develop in space structures as well. Lockheed Martin Space will provide the next generation of 3D printed parts for NASA's Orion spacecraft and carry out research and development projects on manufacturing of thermoplastic components. In Figure 11, docking hatch cover, one of the 3D printing parts produced for Orion, is shown.

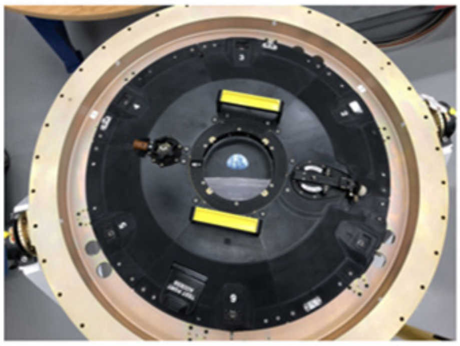

Figure 11: Orion spacecraft part from CF/PEKK [21].

The aerospace industry, trying to increase production efficiency and aircraft construction speed, has applied to various innovations for the design, manufacture, and application of structural components in aircraft construction. One of them is the work done with over molding technology using PEEK. An example of this application is the grid stiffened demonstration panel made of PEEK, shown in Figure 12. Over molding the grid stiffened demonstration panel combined elements of press forming and injection molding, demonstrating the harmony of the relationship between the two compounds. This work resulted in a part with the material performance of a continuous fiber-reinforced composite and the geometric stiffness of an injected grating. All of this with a cycle time of less than two minutes, significantly saving time.

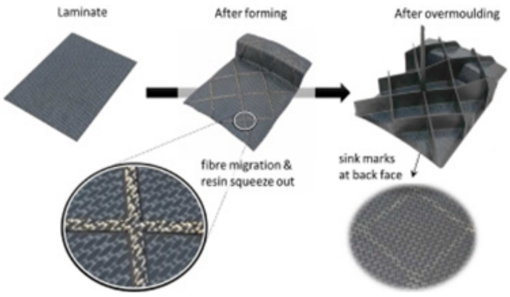

Figure 12: Grid stiffened demonstrator production from CF/PEEK by over-molding technology [22].

LM PAEK is used as UD (unidirectional) tape for the MECATESTERS Clean Sky 2 large passenger aircraft attempt project which was one of the first laminates manufactured in terms of this Clean Sky 2, 30-months long project [23].

LM PAEK was introduced in the TAPAS 1 development program. Airbus Nantes exhibited a fuselage panel with integrated stiffeners at the 2013 Paris Air Show. It is fabricated using the CF/LM PAEK tape supplied by TenCate, with press-formed omega and butt-jointed T stringer elements that were welded to the skin, made with automated fiber placement (AFP). AFP, stamp forming, and welding processes work very well with LM PAEK. LM PAEK has some advantages particularly for automated processing methods such as automated tape laying (ATL). Figure 13 shows a laminate made using ATL and a press-formed rib.

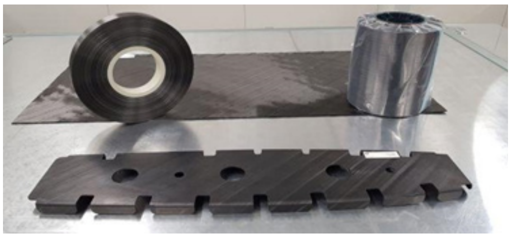

Figure 13: Slit CF/LM PAEK tape [24].

Globally, the aerospace and defense industries use mostly PPS composites. They have also been approved for use in circuit boards, sockets, plug-ins, electronic components, and defense airplanes by some of the institutions [25]. The leading edge structure of the A380 shown in Figure 14 and A340-500/600 wing is made of PPS glass carbon fiber composites as well the rudder, elevator of the G650 are made of PPS carbon fiber composites [26].

Figure 14: A380 Welded fixed wing leading edge from PPS [27].

Commonly used manufacturing methods for thermoplastics which require high heat and pressure such as thermoforming, compression, and injection molding are likely applicable for PEI and the properties aforesaid create a wide range of applications and production possibilities. This material has many advantages, especially at high temperatures, it is resistant to long-term work and is successful in keeping its mechanical properties stable. Especially with 3D printer technology, companies are providing new studies to the literature by signing many firsts in the aerospace sector. Using this material fast and high quality prototypes, tools and small volume parts are produced. One of the most interesting studies in this field is the world's first 3D-printed jet powered unmanned aerial vehicle (UAV), carried out in collaboration with Aurora Flight Science and Stratasys. 3D printed PEI based parts forms 80% of the general parts of the UAV. This arrangement provides a lightweight and fast produced UAV where the lightness supports higher flight speeds. The unmanned aerial vehicle made from can be seen in Figure 15.

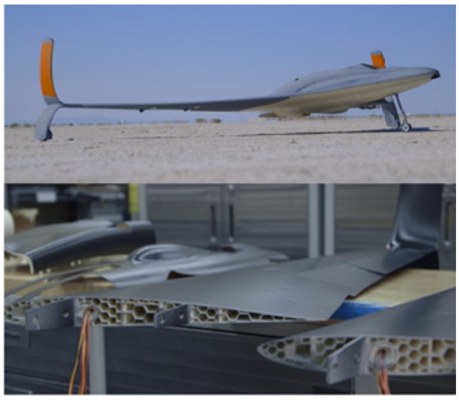

Figure 15: 3D printed PEI based UAV [28].

ABS generally appears as a lightweight alternative to traditional aerospace materials and is used in applications where strength or high temperature is not a very important factor. However, it is also suitable for use in important parts by gaining some desired properties with the additions made of it. ABS and mixtures of ABS with other thermoplastics are generally used in interior cabin applications in commercial aviation aircraft, due to the chemical and flame resistance they provide. ABS is preferred as thermoplastic, especially in parts that do not affect the general use or structural strength of the aircraft, but need to be lightened and a material with sufficient strength is used, which is affordable, long-lasting, easy and cheap to repair and maintain. CF-ABS thermoplastic composite sandwich structure was then used as a Dual-Tilting Clamp part of Quadcopter unmanned aerial vehicle and tested. In the tests, it has been proven that the produced part is more robust and long-lasting than the old monolithic parts [29]. Figure 16 shows some fuselage parts which are printed with 3D fusion deposition modeling (FDM) method.

Figure 16: Fuselage parts made from ABS [30].

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Conclusion

TPC materials are rising as an important alternative to traditional materials in the aerospace industry with the advantages they provide today. In this study it is seen that recyclable, easily shaped, weldable, lightweight and durable TPC materials have become an important research and application subject in the aerospace industry through the years. In this context review of some important projects and structures were carried out. Also it is concluded that 3D print technology is very applicable with thermoplastic composites for UAV and other aerospace applications. In addition, they seem to be very valuable for future projects due to their recyclability properties. With the increase in R&D activities, the use of thermoplastic composites in aircraft structures should be increased to start an advantageous period in terms of economy and environment in the aviation and space sector.

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