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WELDING OF THERMOPLASTIC POLYMER COMPOSITES IN THE AIRCRAFT INDUSTRY (Review)

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The volume of polymer composite structures in the aircraft industry is steadily increasing. Polymer composites based on thermosetting matrices are traditional in this field, but it is important to use new thermoplastic composites (TPCs), which have several advantages over thermosetting ones. The use of thermoplastic composite materials makes it possible to actively use welding processes in the production of structures, which significantly increases the productivity of work and reduces their cost. In the aircraft industry 3 types of heat-resistant polymers of the class of polyarylene are mostly used: polyetheretherketones (PEEK and PEKK), polyetherimide (PEI) and polyphenylene sulfide (PPS). Aeronautical structures are characterized by a large variety and complexity of forms, that's why almost all known methods of plastic welding are involved for joining. The resistance welding of polymer materials applying embedded elements made of metal mesh or carbon fabric is actively used. Induction welding technology is suitable for joining structures made of conductive carbon composites. Ultrasonic welding, laser welding, and indirect-heated tool welding are also used in aircraft engineering. Nowadays, welding processes are usually digitally controlled with permanent data storage, but currently the agenda is to move to linear process control using temperature monitoring. This paper, based on the materials of European publications, presents examples of the application of different welding methods in the manufacture of structures made of modern polymer thermoplastic composites in the aircraft industry. 16 Ref., 9 Figures.

Keywords: polymer composites, thermoplastics, welded joints, resistance welding, induction welding, ultrasonic welding

The leading aircraft manufacturer SE Antonov actively cooperates with the institutes of the National Academy of Sciences of Ukraine in order to develop and implement the advanced aircraft technologies. One of the directions of such work with the E.O. Paton Electric Welding Institute is the preparation of new polymer composite materials for the use in domestic aircrafts [1].

In modern aircraft construction, many of aircraft parts are made of polymer composites — fibrous or fabric materials impregnated with polymer matrices. The use of composites can significantly increase the weight efficiency of aerospace vehicles. In the future, their share in aircraft structures will reach 70–75 % [2]. In this field, the polymer composites are traditionally used, which are based on thermosetting matrices, however, the use of new thermoplastic composites (TPCs) is constantly growing, which have a number of advantages over thermosetting ones.

The main incentive for the use of TPC in the aircraft industry is the ability to join parts of them by welding. The welding process is a much better alternative to the traditional methods of joining parts made of thermosetting composites — mechanical mounting and adhesive bonding. Other advantages of TPC are the ability of remolding (remelting) in the process of repair and disposal, formation without complex chemical reactions and long hardening processes, no need in special storage conditions and almost unlimited storage period. This article provides a review of the main welding methods of polymer thermoplastic composites, which are used in the modern aircraft industry.

As far as aircraft elements usually operate in extreme conditions of mechanical and thermal loads, thermoplastic composites for aircrafts are made on the base of strong and heat-resistant polymer matrices. Along with traditional polycarbonates and polyamides, in this field three types of polyarylene class compounds are widely used. They include polyetheretherketones (PEEK and PEKK), polyetherimide (PEI) and polyphenylene sulfide (PPS) [3]. Polyarylenes represent carbocyclic polymers, in the molecular chains of which ring benzene nuclei are present, which represent a stable chemical structure and provide a polymer with a high thermal stability.

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Polyetherketone monomers in various combinations, consist of three main components: a simple ether group, an aryl cyclic hydrocarbon group and a ketone organic compound with a double chemical bond. Depending on the number of components in the monomer, polyetherketone (PEK), polyetherketoneketone (PEKK), polyetheretherketone (PEEK) and the like are distinguished. All these polymers have a melting point higher than 330 °C and can be used as TPC matrices.

Polyetherimide (PEI) monomers also consist of three main parts: a simple ether group, an aryl ring group and an imide group derived from carboxylic acids. PEI is a high-quality fire-resistant thermoplastic matrix for TPC, which belongs to the group of heat-resistant plastics with heat resistance of up to 200 °C. It has high mechanical strength, dielectric strength, resistance to hydrolysis, ultraviolet and gamma radiation.

Polyphenylene sulfide (PPS) monomers have the simplest structure and consist of an aryl group and a sulfur atom. PPS is a relatively cheap and high-quality polymer, which is very strong, hard and dense and has a natural fire and heat resistance at the temperatures of continuous operation, being significantly higher than 200 °C. PPS is also resistant to oxidation and chemicals, it absorbs a minimum amount of water, has good electrical and excellent technical properties, as well as a low probability of deformation [4].

The vast majority of polymer structures of a modern aircraft are made of prepregs, sheet composite semi-finished products. Prepregs are produced by impregnation of the fibrous base (carbon or glass cloth of a special weaving) uniformly distributed in a layer of a polymer matrix. The leading manufacturers of modern composite materials, both thermosetting and thermoplastic, are the Companies TenCate Advanced Composites and Porcher Industries [5, 6]. Thermoplastic composite materials are available in the following forms:

● semipregs are the fabrics and unidirectional fibrous tapes, having a polymer matrix layer located only on their surface;

● prepregs of a fabric and unidirectional fibrous tapes, which are completely impregnated with a matrix polymer;

● thermoplastic laminates are a form of the material, which consists from 1 to 24 layers of reinforcing material impregnated with a thermoplastic binder. They are combined into flat sheets.

In a limited number, welded structures of TPC have been already long time used in aircraft industry and aircrafts with TPC parts have been in operation for many decades. Currently, aircraft manufacturers mostly use resistance welding and induction welding of polymer materials. Also, ultrasonic, laser and conduction welding are used [7].

The essence of resistance welding consists in the fact, that heat is produced by a flat embedded resistive element, which is located at the interface and remains inside the weld. The electric current passing through the resistive element generates heat and melts thermoplastic polymer. The working pressure on the outside of the part promotes the formation of a welded joint after switching off current and hardening the molten polymer (Figure 1). The embedded elements, usually in the form of a tape, are made of metal mesh or electrically conductive carbon fabric.

At the Berlin Air Show in 2018, Premium AEROTEC Company (Augsburg, Germany) presented a demonstration model of the bulkhead of A320 Airbus (Toulouse, France). The bulkhead consists of eight pressed segments based on TPC of carbon fiber/PPS, jointed by the method of resistance welding. On

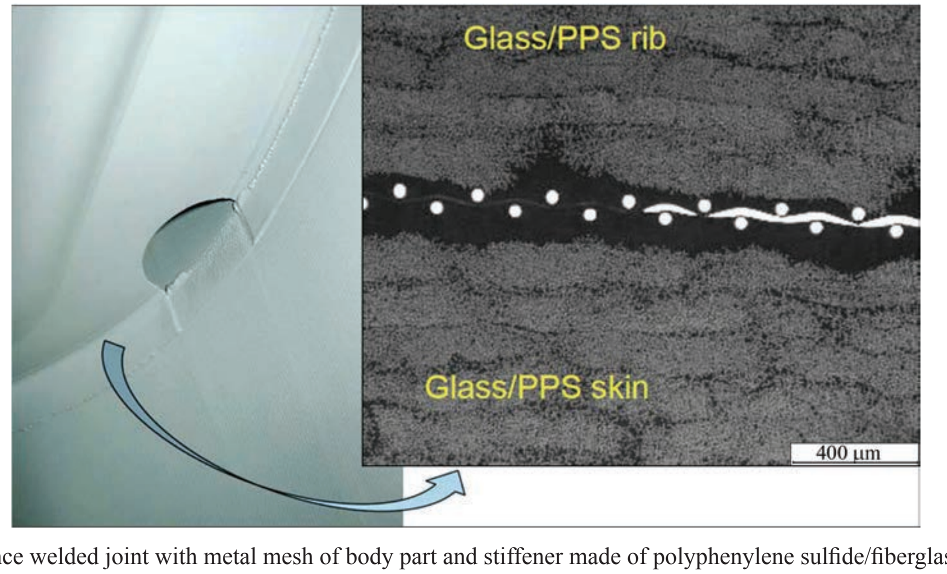

Fig re 1 Resistance welded joint with metal mesh of body part and stiffener made of polyphenylene sulfide/fiberglass composite [8]

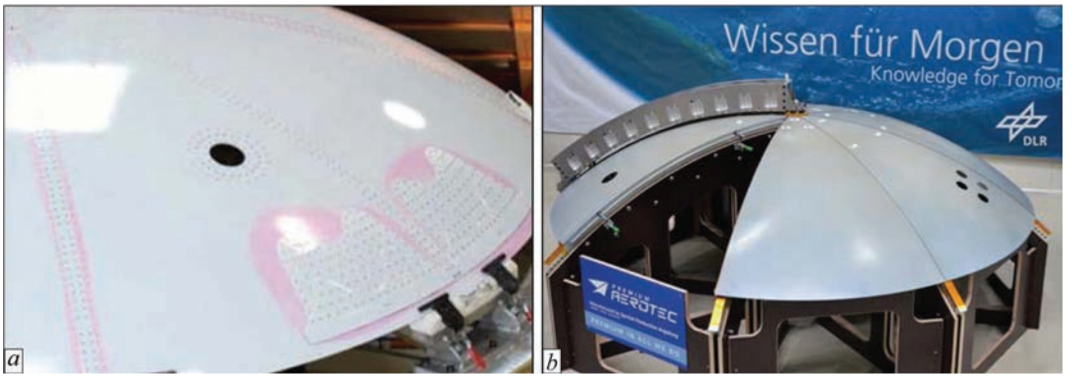

Figure 2. Demonstration model of bulkhead of Airbus A320: *a* — acting version made of aluminum with a large number of rivets; *b* — welded demonstration model without rivets with «welding bridge»

a demonstration model of Premium AEROTEC, the length of the welds was about 1.5 m.

The thermoplastic composite bulkhead of A320 produced by welding offers the decision without rivets as compared with an existing aluminum design (Figure 2). The use of welding in this case allows saving weight, time and cost of positioning and drilling holes, as well as the cost of mounting. As embedded elements during welding, carbon fiber tapes served.

An important element of resistance welding is the working pressure, which should be applied to the parts to produce a good joint. For small parts, the working pressure is usually created by means of a robot manipulator. For large parts it is necessary to create special equipment that will provide a uniform pressure along the entire weld. In this case, the working pressure provided a bent metal «welding bridge», designed by Premium AEROTEC. By its rotation it occupies the position over each of the eight welds and creates a uniform working pressure by ten pneumatic cylinders located on it [9].

During induction welding, the coil supplied by a high-frequency alternating current, moves along the welding line and induces eddy current in the electrically conductive fibers of a carbon composite. To generate eddy current in carbon fibers, AC voltage of up to 1 MHz frequency is used. TPC based on fiberglass, which does not conduct electric current, are unfit for induction welding [10].

Figure 3. Production of elevating rudders and yaw rudders by the method of induction welding from TPC carbon fiber/PPS for Dassault Falcon 5X jet aircraft

Using induction welding, the Company KVE Composites helped to implement the technology of production of elevating and yaw rudders for the aircrafts Gulfstream G650 and Dassault Falcon 5X [11] (Figure 3).

The Company Composite Integrity (Porquette, France) used an alternative approach and developed the technology of «dynamic induction welding», which is applied by the Company STELIA Aerospace (Toulouse, France) for joining stringers and fuselage shells based on unidirectional carbon tape and PEKK. As far as induction units, generating eddy current during welding of materials with unidirectional tapes, are absent, a special multibeam induction coil was developed. In 2016, Composite Integrity implemented the technology of induction welding to manufacture hatches for access to fuel tanks from TPC in the aircraft Airbus A220 (Figure 4).

KVE Composites showed that the use of hatches, produced by welding from TPC, allows saving costs. Even small planes can have up to 60 such access panels. Moreover, all of them have different shapes and are manufactured using a composite sandwich structure with a honeycomb core. By means of welding, all access panels can be manufactured on a one industrial site. Moreover, there is no need to perform treatment of the core. Here, the components are used, similar to the construction set LEGO: flat sheets and stamped stiffeners, which are welded with each other and form different shapes. The welding tools are relatively cheap as compared to those used today. Using welding, it is possible to manufacture all aircraft access panels of various types from TPC with the expenses on equipment, not exceeding 100 thou US dollars, which is a significant saving [11].

In 2015, the Company Composite Integrity started its work on the Project STELIA Arches TP and developed equipment for induction welding of bent parts with the size equal to that of an aircraft fuselage (Fig-

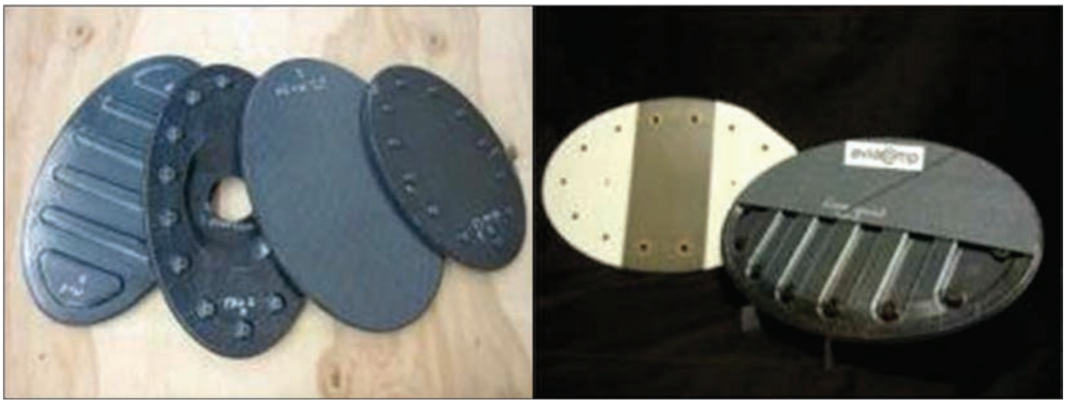

Fig re 4 Fuel tank access hatches for narrow Airbus A220 aircrafts, made of TPC by the Company Aviacomp using induction welding technology developed by the Company KVE Composites

ure 5). The welding process was called «dynamic», because the robotic installation welds stringers along the length of the fuselage, the induction coil moves in three coordinates during welding, including the vertical z direction. The stringers and lining in the demonstration model of STELIA have a variable thickness. The aluminum guide serves as a clamping device and prevents the displacement of the stringer relative to the lining during welding. In the demonstration model, the working pressure was applied by means of two rollers on the welding head, which were placed above the coil. During welding, the rollers run along the stringer near the rail–clamping device, while the coil moves along the weld line. Currently, a new induction welding head was patented, which uses a single roller and improves the mechanical properties of the weld. The installation is also equipped with a device for cooling the weld, which supplies air to the surface of the joint, brings its temperature to the level lower than the crystallization limit and prevents the risk of divergence of weld elements after release of working pressure [9].

The Company GKN Fokker has gained an extensive experience in using another widespread method of welding parts from TPC: ultrasonic welding. The installation for ultrasonic welding includes electric generator of high-frequency (20–40 kHz) oscillations, piezoelectric transducer and sonotrode, which contacts with the surface of a part and provides heating and melting of a polymer matrix under the action of mechanical ultrasonic oscillations. This method was traditionally used for welding spot or small-length welds [11].

In the aircrafts Gulfstream ultrasonic welding was used to produce more than 50000 polymer parts of floor panels, manufactued from TPC by injection molding. Notwithstanding the advantages of spot welding, the ultrasonic method is very fast and highly

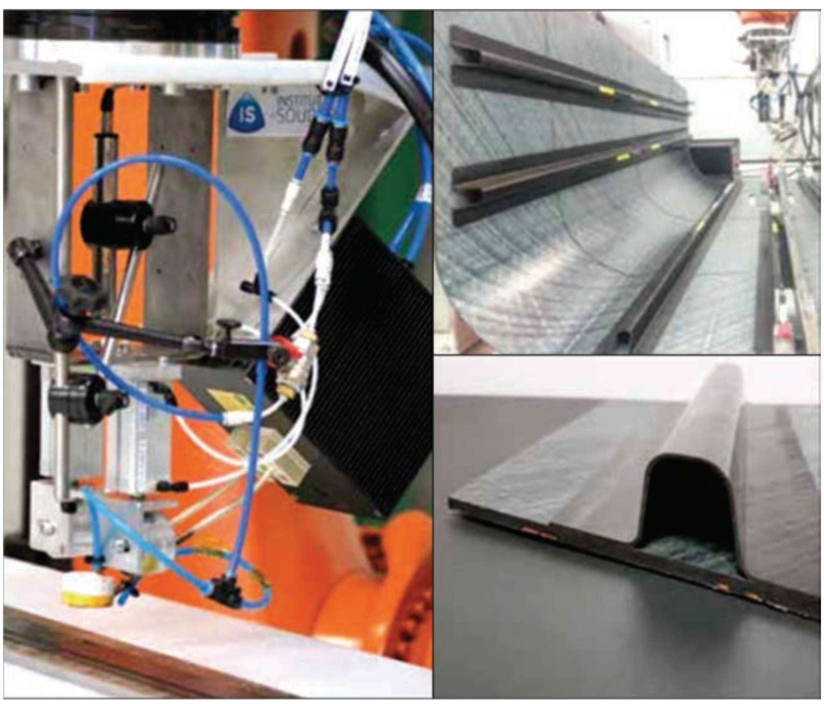

Fig re 5 Induction coil and technology of welding stringers based on unidirectional carbon fiber and PEKK with lining developed by the Company Composite Integrity

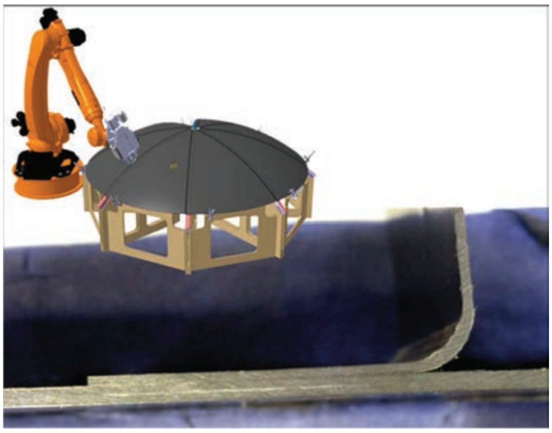

Figure 6 Ultrasonic welding head of the DLR-center and specimen of welded joint from TPC on the base of unidirectional carbon fiber and PEKK for tests on L-tear [9]

automated. The brackets of an aircraft fuselage are often joined by rivets or bolts with large structures made of thermosetting composite. Ultrasonic welding allows providing a very good joining of brackets, which are often made of nonreinforced thermoplastics.

The ultrasonic welding head of the DLR center (Augsburg, Germany) was also demonstrated, which was installed at the industrial robot KUKA and designed as an alternative to resistance welding for welding the bulkhead of the A320 aircraft from TPC (Figure 6). The mechanical tests on L-tear and comparison with the strength of mechanical joints showed promising results.

At the «31st Technical Conference, ASC» in 2016, the specialists from the TU Delft (Delft, the Netherlands) stated in their report that ultrasonic welding can be expanded to elongated welds by forming a continuous line of adjacent weld spots, which are partially overlapped. Such a continuous ultrasonic welding with producing successive points was used in the laboratory conditions to manufacture a demonstration model of the panel of the Clean Sky EcoDesign glider from TPC (Figure 7) [12].

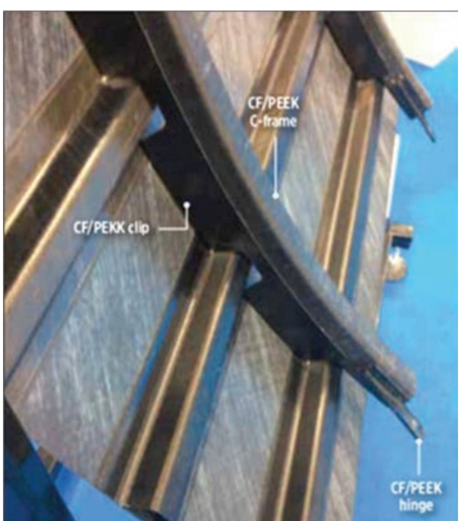

Figure 7 Sequential ultrasonic spot welding of elements made of TPC carbon fiber/PEEK

Many cast polymer brackets of the Fokker aircraft are transparent to the laser. Therefore, there is a great potential in the use of laser welding for fixing those brackets to the fuselage structure of a carbon fiber without the need in drilling holes. The type of reinforcement and the thickness of the laminate affect the quality of the weld. However, LZH Company demonstrated good results in laser welding of PPS and PEI laminates reinforced with fiberglass.

LZH Company patented the laser technology and won the 2018 JEC World Innovation Award in the category of aerospace applications for «Modular Thermoplastic Stiffening Panels», where a stamped stiffening mesh based on thermoplastic carbon fiber is welded-on by laser to a composite shell [11].

As an alternative to induction welding, GKN Fokker Company developed a new technology for indirect heated tool welding. On the principle of «iron», the heated tool is applied to the outer surface of one of the parts and heats it through, melting the thermoplastic and partially melting the material of the lower part. The method is similar to the known method of thermal pulsed welding of polymer films. A low-inertia heater is used, due to that its heating up and cooling down takes only a few seconds. Since the entire tool is heated at once, the welding time does not depend on the length of the weld, it is the same also for the length of 0.5 and 10 m. At the exhibition JEC 2014, the fuselage panels of TPC were presented, manufactured with a heated tool. This method can work well during welding stringers of 6–10 m long with the fuselage lining (Figure 8) [11].

A key aspect for the introduction of welding technology in the manufacture of aircraft fuselage structures from TPC is the ability to monitor welding process and perform its real-time control. Nowadays, welding processes are usually digitally controlled with permanent data storage, but currently the agenda is to move to linear process control using temperature monitoring. It is supposed that the development of such technologies for resistance and induction welding requires several years, and for ultrasonic welding it may appear very quickly. Monitoring of the process of sequential spot ultrasonic welding is possible on the basis of analysis of power and shear curves, which are produced by the welding machine and allow a quick determination of the optimal welding parameters. The specialists of the aircraft industry believe that launching of welded large elements of the aircraft fuselage and possibly all welded fuselage, having no mechanical fasteners, into production will take place in the near future [11].

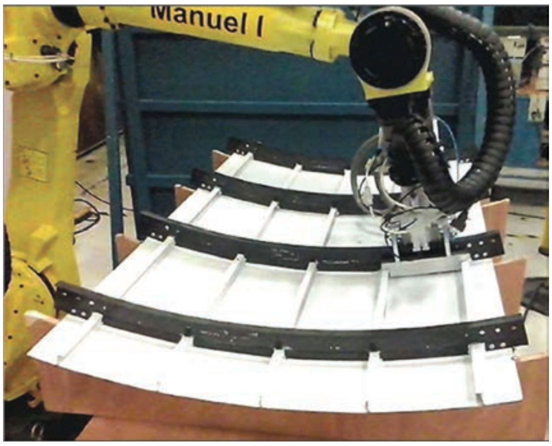

Figure 8. Robotic head for welding elements of fuselage stringers with a heated tool using indirect heating

In the future, the introduction of additive technologies in the aircraft industry, which are currently developing in a rapid pace and introduced in the production processes of many industries, is also promising [13]. In aircraft and aerospace field, designing, development and production of complex and replaceable parts is one of the relevant issues of modern and future application of 3D printing technologies with the use of polymer materials [14], which is caused by the possibility of a significant reduction in the weight of the parts, manufactured by 3D printing, maintaining their performance characteristics [15]. Also, the parts, created by 3D printing methods are increasingly used in the manufacture of UAVs (Figure 9) [16].

Conclusions

A significant part of modern aircraft structures is manufactured of thermoplastic polymer composite materials based on polyetherketones, polyetherimide and polyphenylene sulfide. To join parts made of these materials, resistance, induction, ultrasonic, laser and indirect heated tool welding are used. The main areas of improvement of welding and production processes in this area are considered to be the transition to real-time process monitoring using temperature control and application of additive technologies.

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Figure 9. UAV in which 80 % of parts are printed of polymer materials

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