Mechanical Investigation of resistance welded high-performance reinforced thermoplastics

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Abstract:
Welding technologies for CFRTP`s offer the possibility for clean, high-strength, structural connections without weakening the initial fiber structure. Joining methods such as implant resistance welding are capable of producing a closed and fiber-fair structural connection of thermoplastic component parts. This paper deals with the implant resistance welding of carbon fiber-reinforced polyetherketoneketone (CF/PEKK). Welding elements were optimized as well as destructive and non-destructive investigations were made to improve the process performance of resistance welded specimen. The influences of different currents were investigated and welding strengths of 58 MPa were achieved.

Keywords: Resistance Welding, Polyetherketoneketone, Joining, Welding Element

Introduction

The combination of In-situ consolidation and welding of thermoplastic composites (CF/PEEK, CF/PEKK, CF/PPS) provides the framework for efficient production of a thermoplastic fuselage without the need for additional, weight-increasing joining elements. Well-known welding technologies such as implant resistance welding or ultrasonic welding are of increasing interest for such an application, facilitating high-strength, sealed connections between two thermoplastic composites. Furthermore, new materials and technological improvements open up new fields of application. This paper presents the influence of process time and current on the resistance welding process of carbon fiber reinforced PEKK.

Resistance Welding of Thermoplastic Composites

Resistance welding is a reliable and repeatable process and for GF/PPS, having already been applied in series production for the Airbus A340 and A380 wing leading edge (J-Nose) [1], [2]. A welding element consisting of an electrical conductive material with additional thermoplastic matrix material is applied in the welding zone, as shown in *Fig. 1*. In the case where the parts to be welded are themselves electrically conductive, additional material for electrical insulation becomes necessary to prevent from current leakage and homogenize the heat development in the joining zone. A constant current flow through the heating element leads to Joule heating of the electrically conductive material and melts the adjacent welding partners. The pressure applied to the weld seam provides a consolidation of the welding partners.

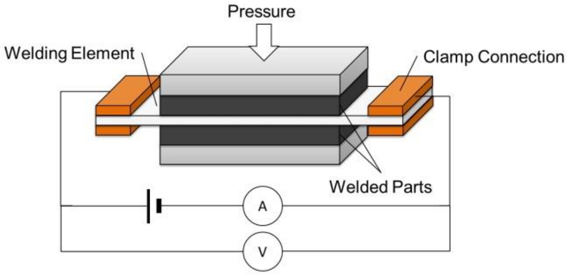

Fig. 1: *Resistance welding – schematic setup (adapted from* [3] *cited in* [4]*)*

Experimental Facility

Welding Elements

The welding elements consist of seven layers. In the center is a stainless steel mesh with a mesh size of 0.3 mm and a wire diameter of 0.065 mm. On both sides of the mesh is one 50 µm layer of PEKK film. For electric isolation between the welding partners and the metal mesh, a PEKK-glass-fiber fabric is added on both sides. A final layer of 50 µm PEKK foil completes the welding element layup. After stacking, the elements are consolidated with a hot press. A 300 x 300 mm² plate of welding element material is produced during a single press. The process of consolidating decreases the occurrence of pores and other imperfections which reduce the final weld quality and hence part performance. For the quality assurance of the welds, microscopy samples are prepared and assessed using a Keyence

VHX5000 microscope. *Fig. 2* shows a 200-fold magnification of a welding element cross-section.

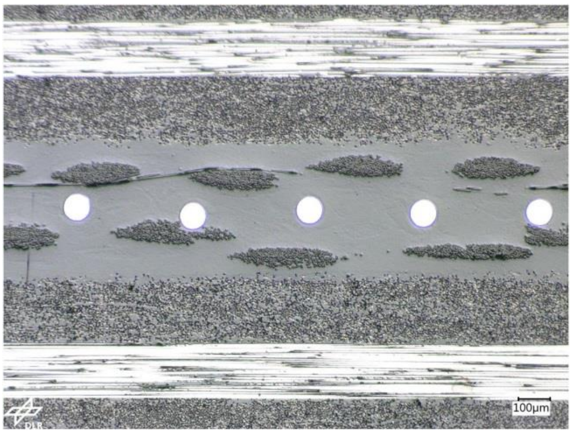

Fig. 2: *Micrograph of a CF-PEKK weld with 200-fold magnification*

The white circles represent the stainless steel mesh. The elliptical clusters are the glass rovings of the GF/PEKK Prepreg. The 90° glass layer is indicated in the upper part. In between is the non-porous matrix area. The upper and lower regions in *Fig. 2* show the 0° and 90° layers of the welded laminates.

Laminates

The laminates are made of twelve layers of unidirectional carbon fiber-reinforced PEKK tapes manufactured by Toho Tenax. They are stacked as a $[0° \; 90°]_{3S}$ layer formation. Additional there are extra layers of PEKK foil on the outer sides for better surface quality. The consolidation is accomplished through a process using a Dieffenbacher hot press. After the pressing process the CF/PEKK laminate has a thickness of 2.5 mm. The press can produce laminates up to a size of 640 mm x 640 mm. In order to be able to assess the quality of the plates, they are tested by means of a non-destructive testing method in the form of ultrasonic scanning (US). After testing, coupons are cut by a WARICUT HWE-P 2015 JetCut system of H.G. Ridder to the dimensions of 200 mm x 40 mm.

Test Rig

The resistance welding apparatus uses two 50 mm diameter piston rod cylinders for the contact pressure and a 125 mm diameter piston rod cylinder which generates the necessary welding pressure. The apparatus is displayed in *Fig. 3*. Pneumatic actuators are connected to the compressed air system, which provides a maximum pressure of 10 bar. The electrical power is provided by two Elektro-Automatik PS 9080-200 4HE power supplies, with a maximum power of 12 kW. The electrical system is controlled by a LOGO! 7 control unit which records the current, voltage and resistance data. If required, up to four type K thermocouples can also be connected to the control system.

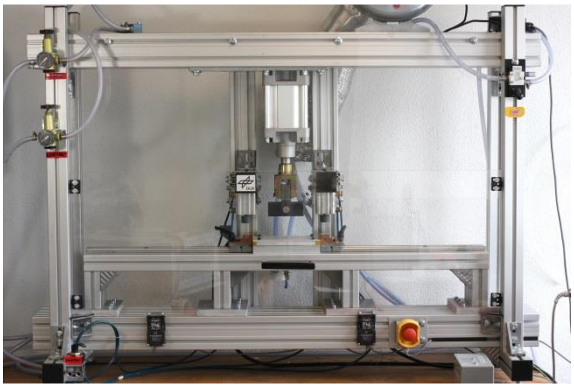

Fig. 3: *Welding test rig*

Welding Tests

In order to carry out the welding tests, two laminate coupons and a welding element are assembled in the sandwich arrangement shown in *Fig. 1*. Welding pressure and contact pressure are then applied. In preliminary tests it was determined that the welding pressure in the range of 0.3 MPa and 0.7 MPa has only negligible effects on the strengths in the specimen area. At a pressure of 0.5 MPa, ultrasonic scans showed that the weld was more homogeneous than at a welding pressure of 0.3 MPa. Above 0.5 MPa no major changes in welding homogeneity were noticeable. Therefore, the welding pressure was constantly set at 0.5 MPa. Freist [5] defines a plateau between 0.5 MPa and 1.8 MPa for the contact pressure. From a contact pressure of 0.8 MPa only small changes in the contact resistance occur, whereby the contact pressure was set to 0.8 MPa. After applying the pressures, the test is run with the process time and current previously set in the LOGO. After the process time is reached and the energy input has been completed, the welding partners cool down under pressure for three minutes and can be removed. For the influence of the welding current on the strength of the weld, the current was varied between 40 A, 44 A and 48 A. In preliminary tests the welding time up to the processing temperature of 380°C was determined. For the lowest tested current with 40 A, a welding time of 60 s was evaluated. At 44 A the heating took 40 s and at 48 A the duration till 380°C was 34 s. Each experiment of the series was repeated four times.

Mechanical Testing Methods

The strength of the weld is investigated via pressure-shear tests following the ASTM norm D3846 "In-Plane Shear Strength of Reinforced Plastics". According to this standard up to six samples are cut out of one welding experiment. This is used to assess the homogeneity of the strength over the welded area. In two out of four repetitions three samples were cut out of the center of the weld (1-3). In the other two repetitions six samples each were cut out near the contact area (L, R 1-3). *Fig. 4* shows the position of the investigated areas on the welded coupons.

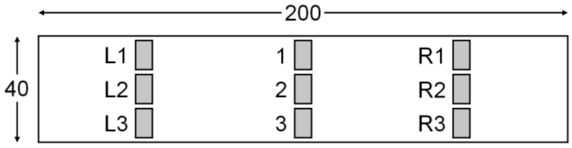

Fig. 4: *Position of the areas tested in the welded coupons*

After cutting, the samples had to be notched. The samples were 80 mm long and 11 mm wide with an overlap of 6.4 mm. For testing a 100 kN Zwick-Roell hydraulic tensile testing machine was used. Additionally the support jig of the ASTM standard was applied. The testing speed was at 1.3 mm/min according to the standard. To determine the strengths, the recorded maximum forces were related to the corresponding fracture surfaces.

Results

In-Plane Shear strength Performance

The in-plane shear strength (IPSS) results of the investigated parameters are shown in *Fig. 5*. Weldings performed with a current of 40 A achieved IPSS of 58.4 MPa. Weldings with currents of 44 A and 48 A achieved averages of 56.6 MPa and 58.5 MPa. The standard deviation of the investigated parameters of 40 A, 44 A and 48 amounted to 4.3 MPa, 5.4 MPa and 3.3 MPa. In addition to the welding results, the material reference of CF-PEKK laminates is shown in *Fig. 5*. The IPSS of the reference material was at 68.9 MPa with a standard deviation of 1.8 MPa and was also achieved following the ASTM D3846.

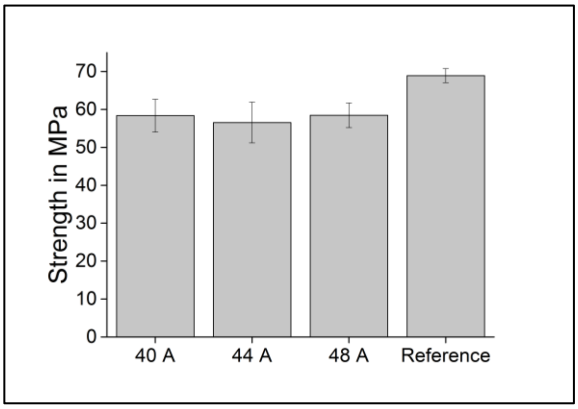

Fig. 5: *IPSS of welding specimen at different welding currents and material reference*

The averages of IPSS of the investigated parameters show just a slight deviation from each other. They are 15 % lower than the reference strength of the laminates. As mentioned in the previous paragraph, test specimens have been taken at various points of the weld. Here, too, the differences are small. Only the right side of the weld, with an average value of 55.6 MPa, has approximately 3 MPa less strength than the middle (58.9 MPa) and left side of the specimens (58.5 MPa).

Energy input during the welding process

As the current and resistance were recorded during the welding process, the welding power can be estimated. Multiplied by the duration of the respective process, the energy input was calculated. The corresponding formula is:

$$E = P \times t = I^2 \times R \times t \ \text{[kJ]},$$

with power P [W], duration t [s], current I [A] and resistance R [Ω]. The calculated energy input is visualized in *Fig. 6*.

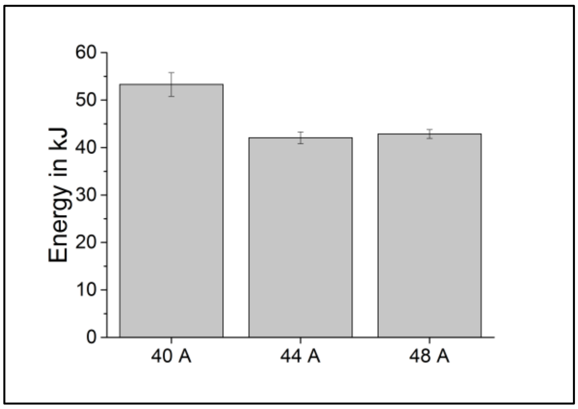

Fig. 6*: Energy input of welds with currents of 40 A, 44 A and 48 A*

The average energy input of tests with currents of 40 A and durations of 60 s is 53.3 kJ with a standard deviation of 2.5 kJ. The average of processes with 44 A and 40 s duration is 42.1 kJ with a standard deviation of 1.2 kJ. The processes of the highest investigated currents of 48 A and the shortest duration of 34 s had an energy input average of 42.9 kJ with a standard deviation of 0.9 kJ.

Failure Modes

The samples tested have two different types of damage. On the one hand is the type of interfacial failure and on the other the types of intralaminar failure. Interfacial failure occurs at the interface between the laminate and the welding element. In the case of intralaminar failure, a distinction must be made between failure in the layers of the welding element and failure in the laminate. Examples of failure types are shown in *Fig. 7*.

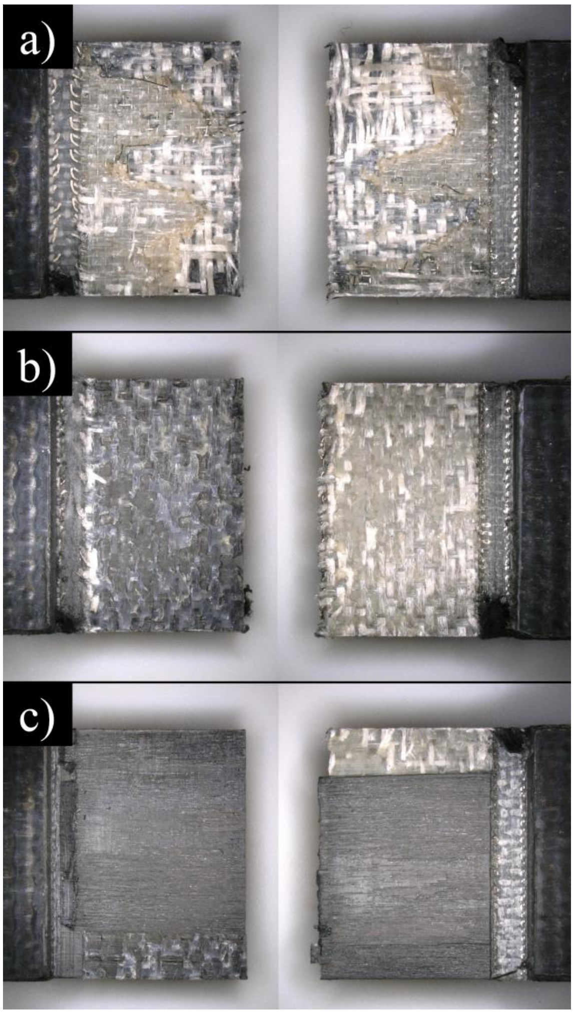

Fig. 7: *Failure Modes in welded specimen pairs:*
a) Intralaminar failure in the welding element,
b) Interfacial failure, c) Intralaminar failure in the laminate

Overall, intralaminar failure in the welding element was most common with 34 cases. This is also where the highest strengths are created. Interfacial failures occurred 17 times. It indicates that the energy input in the examined area was too low, which means that a loss in strength must be expected. Intralaminar failure in the laminate has occurred three times. Since the strength values of this type of failure are lower than the other failure types, it was assumed that there were defects in the laminate. Therefore, these values have not been included in the valuation.

Conclusions and Outlook

The main reason for the similarity of the values can be found in the process time. The results show that good values can be achieved with both short processes (34 s) at high currents and long processes (60 s) at low currents. The energy input analysis showed similar levels for the short processes. With longer processes however 25 % increased energy losses were observed. The energy losses depend on the temperature difference between the welding and the test setup. Losses increase at higher temperatures. Since the slow processes remain longer in the high temperature range, the heat losses increase. With this work parameters were investigated which were located in a process window suitable for the welding process. In further work, the limits of the process window for the resistance welding process of carbon fiber reinforced PEKK must be demonstrated. In addition, the homogeneity of the welding surface must be further improved by suitable process control. This should also lead to a decreased standard deviation of the strength values.

References

[1] “Thermoplastic composites gain leading edge on the A380,” Composites World, Jan. 2006.

[2] G. Aerospace, “GKN Aerospace Programme Data,” Oct. 2015.

[3] D. Stavrov and H. E. N. Bersee, “Thermal Aspects in Resistance Welding of Thermoplastic Composites,” 2003.

[4] D. Stavrov and H. E. N. Bersee, “Resistance welding of thermoplastic composites-an overview,” Composites Part A: Applied Science and Manufacturing, vol. 36, no. 1, pp. 39–54, Jan. 2005.

[5] C.Freist, “C. Freist, Experimentelle und numerische Untersuchungen zum Widerstands-schweißen endlosfaser und kurzfaser-verstärkter thermoplastischer Hochleistungsstrukturen“, Stuttgart, 2013.