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MOLDING AND JOINING OF CONTINUOUS FIBER-REINFORCED POLYETHERETHERKETONE (PEEK)

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Abstract

The paper presents and discusses certain procedures for forming and joining of components made of continuous fiber-reinforced Polyetheretherketone (PEEK). The quality of different welding methods and adhesive bonding is compared with the aid of tensile shear tests.

I. Introduction

Of great importance for the application of continuous fiber-reinforced thermoplastics are forming and bonding techniques which allow maximum exploitation of strength and stiffness of the undisturbed fiber orientation as well as economic processing. The procedures used with short fiber-reinforced thermoplastics can only be applied to a limited extent. The purpose of this report is to present existing procedures and examine their application in the processing of continuous fiber-reinforced polyetheretherketone.

II. Forming Processes

It is of primary importance for forming processes that the desired fiber orientation in the component does not change during forming.

This paper will present component production

- in the mold
- with a layer-up process
- in vacuum

Forming in the Mold

Forming in a Hot Steel Mold With a Hot Semi-Finished Product

CF-PEEK plates can be formed to molded parts in a subsequent step. In doing so it must be kept in mind that the degree to which plates made of UD prepregs can be formed is limited. Sheets can be formed to channel sections, angle sections, and subjected to simple folding without any problem, Fig.1. With spherical forming there is the danger of wrinkle formation; although the surface can be smoothened with an increased molding pressure, the bearing strength of the component is reduced as a result of the wrinkle formation.

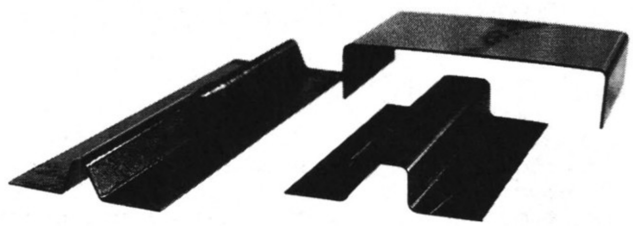


Fig. 1: Parts, Formed in the Mold

The following forming parameters were used for the one dimensional CF-PEEK formed parts:

Forming temperature:	360 °C
Pressure:	5 bar
Speed:	1 mm/sec
Cooling rate:	10-15 °C

When forming to spherical formed pieces in which greater degrees of forming are involved, there is the danger of the fibers in plates made of UD-prepreg being torn apart because of the poor supporting effect of the matrix. This can be seen in Fig. 2. A supporting foil serving as the top layer, for example Upilex foil or possibly CF-PEEK fabric, can remedy the situation. However, CF-PEEK fabric is currently not in production and only a few preliminary studies were conducted with laboratory samples. PEI-fabric prepregs were used for further tests. The results from the forming tests can be applied to PEEK since the same type of fabric was used.

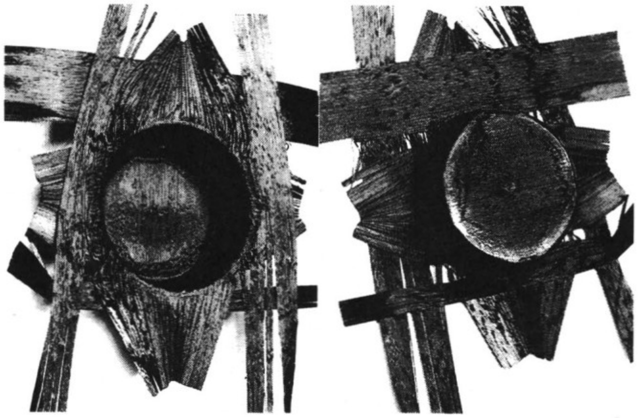


Fig. 2: Formed Part, Made of UD-Prepreg

The excellent forming properties of fabric reinforced thermoplastics are shown in Fig. 3. It is important that it must be a twill fabric. With components made completely of fabric prepregs it is possible to prevent wrinkling; in special cases controlled guidance of the plate to be formed can significantly reduce or prevent wrinkling.

Forming in a steel mold is a process with good reproducibility. A 100 % molding charge is necessary when the fiber content exceeds 50 vol% . If there is too little material at particular points in the cavity there is the danger of the layers separating at these points and air being trapped inside. If there is too much material, the mold will stick and not close properly.

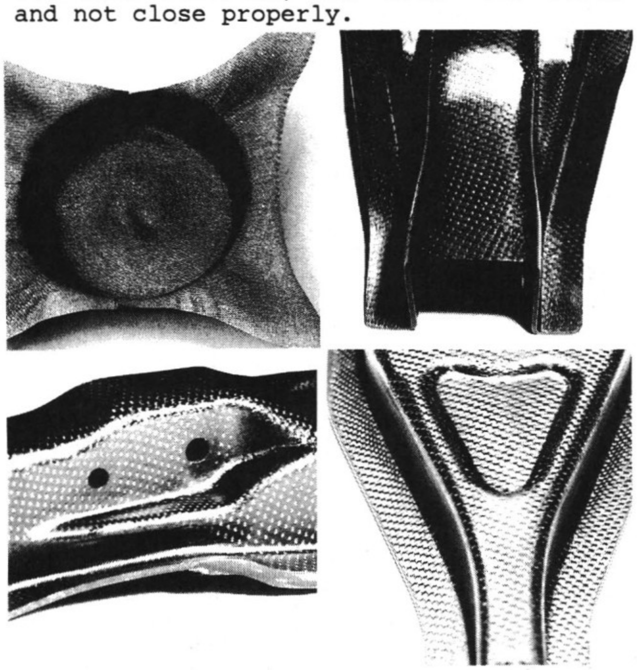


Fig. 3: Formed Parts,
Made of Fabric Prepreg

Forming With a Hot Mold Bottom Part, a Hot Thermoplastic Matrix and a "Cold" Mold Top Part (Steel, Silicone Rubber)

In order to avoid the problems of nonuniform molding charges resulting from variations in thickness of the plates to be formed or inaccuracies in the mold, the use of rubber-coated mold top parts was studied. The types of silicone rubber available today can only be used to a limited extent because they can be exposed for only short periods of time to the approx. 380°C temperature necessary for forming CF-PEEK. It is conceivable that they can withstand approx. 40 cycles at 380°C without their quality being impaired. Using release agents leads to an embrittlement of the rubber.

Forming took place after the mold bottom part together with the CF-PEEK plate was heated to the forming temperature of 380°C. During this process the temperature of the mold top part increased to approx. 120°C. The rubber coated mold top part was inserted in this "cold" condition. Upon contact with the thermoplastic, the rubber prevents the temperature from dropping as quickly as it would be with a "cold" steel mold. Thus the possible forming time is extended, decreasing the danger of damage resulting from an impairment of flow. Looking at the contour of the formed part one can see that the edges of the component are slightly rounded when a rubber-coated mold part is used, Fig.4. The entire surface is good because of the uniform pressure.

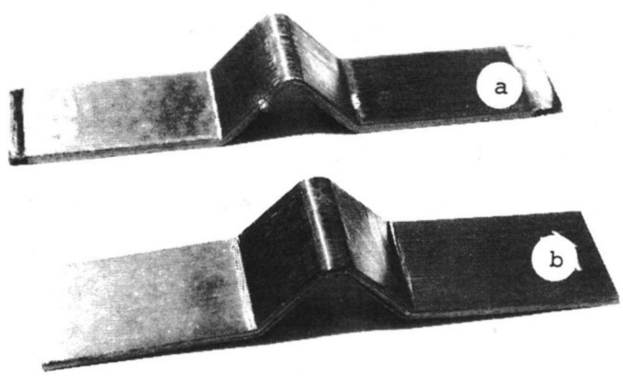


Fig. 4: V-Formed Parts
a) Formed in a Steel Mold
b) Formed in a Rubber Coated Mold

It must be kept in mind that the heating must be switched off as soon as the mold closes and the cooling must be switched on.

Forming by a Lay-Up Process

To be able to simply produce moldings with reproducible strengths, a lay-up method was developed at DFVLR /1/ in which the fiber orientation at corners and in small radii is maintained even with UD-prepregs.

This is a lay-up process in which the prepreg layers are placed one after the other on or into a heated mold, Fig. 5. In this process the individual layers are rolled one after the other onto the heated mold surface. The pressure causes the layer of prepreg to heat up from the underside to the melting temperature and to weld together with the layer beneath it. The upper side does not become immediately tacky due to the poor thermal conductivity of the thermoplastic material. This enables the optimal forming of the prepreg layer to the mold surface with a roller. If in this process the roller is cooled it is no longer necessary to use a release agent. This procedure can also be automated. In Fig. 6 the individual steps are demonstrated on a tie bar section.

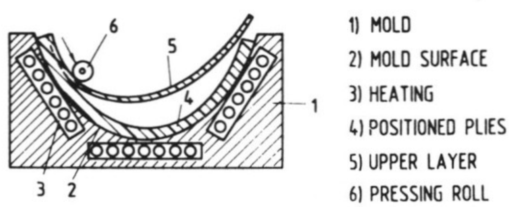


Fig. 5: Lay-Up Process

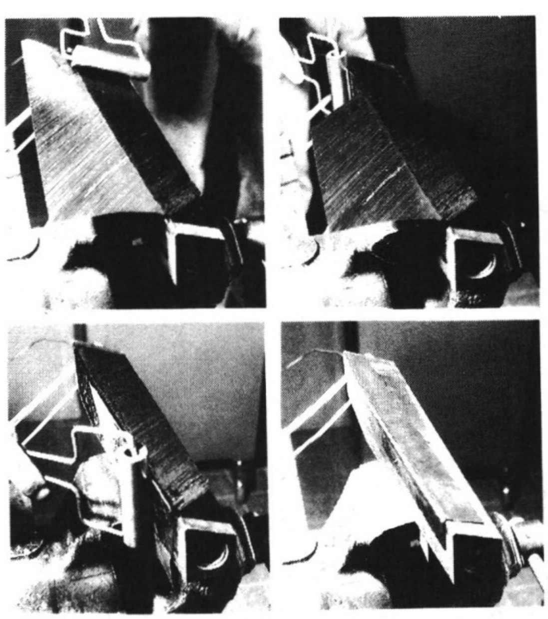


Fig. 6: Lay-Up Process, Manufacturing Steps

In a following step, the part can be consolidated by means of a vacuum or in an autoclave in order to improve the overall quality if this should be necessary.

The forming temperature for working CF-PEEK is 400°C. For wall thicknesses greater than 3 mm the temperature must be somewhat increased. The oxidation which must be expected on the surface can be disregarded if the next layer will be applied within 10-15 minutes. The use of inert gas can prevent or reduce the oxidation of the matrix surface.

Forming in a Vacuum (Diaphragm Forming)

Another method for forming CF-PEEK laminates applies a vacuum. This is a process in which the pre-fabricated plates or prepreg layers which have not yet been pressed can be formed. The material to be formed is layed between two supporting foils, e.g. Supral or Upilex foil, and then the space between these foils is evacuated via a vacuum ring, Fig. 7. The laminate is then heated in an autoclave with two pressure zones, Fig. 8, and then consolidated following the forming phase. When the cooling process is finished the pressure is reduced and the autoclave opened. The process cycle is shown in Fig. 9.

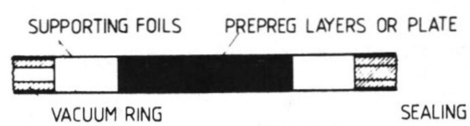


Fig. 7: Diaphragm Forming, Detail /2/

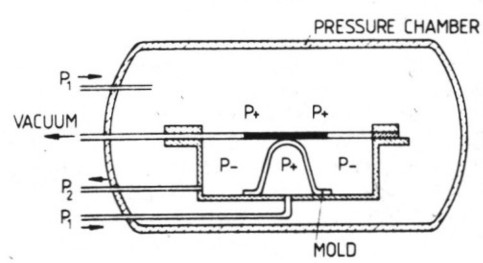


Fig. 8: Diaphragm Forming

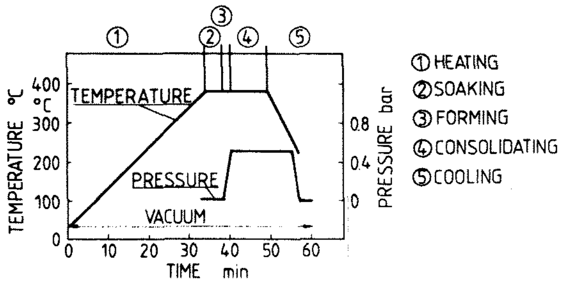


Fig. 9: Diaphragm Forming, Process Cycle /2/

The mold on which the laminate is pressed should be made of aluminium or thin-walled stainless steel.

The forming temperature is 400-450 °C, the total cycle time is up to one hour, using Supral foils. It seems to be possible to reduce this time using Upilex foils. The components are of good quality, however, it is not possible to produce any desired component geometry (elasticity of support foil and shifting of the fibers at sharp edges).

This diaphragm forming is time-consuming and therefore expensive, but it provides means of producing complex components from UD-prepregs.

Comparison of Individual Forming Processes

Forming in the mold is suitable for series production in which the plate material must be formed quickly into a molded part. Wrinkles are not always avoidable despite of all precautions. Beyond a certain degree of forming it is necessary to use fabric prepregs to maintain fiber orientation.

The molds must have an appropriate heating capacity with temperature regulation and cooling, controlled if possible.

Production of components using the lay-up method is recommended if the fiber orientation, for example with primary structures, must be maintained and reforming is not possible without wrinkle formation. The use of UD-prepregs is no problem as long as the inner radii are not less than 3 mm.

The surface quality on the side facing away from the heated mold surface does not entirely match the quality of the parts formed in the mold unless vacuum has been applied or a mold is used for consolidation. The expenditure for heating and cooling is similar to that needed for forming in the mold.

Diaphragm forming is technically the most complicated and expensive method. Its application is appropriate in those cases where none of the other methods can be used.

III. Bonding Techniques

Structures made of more than one component must be joined together by suitable bonding techniques, enabling high loads without damage to the fibers.

Possible joining methods for thermoplastic matrix materials are:

- Heat
  (mold, heating mirror, heating element, hot gas, laser)
- Friction
  (ultrasonics, vibration, rotation)
- Induction
- Adhesion.

Tensile shear tests were conducted so that identical test conditions can be used for comparing all joining processes. Fig. 10 shows the sample geometry. The values thus calculated are suitable for comparative evaluation even if they cannot necessarily serve as dimensioning values.

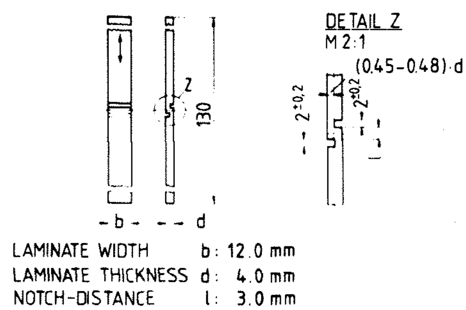


Fig. 10: Specimen for Tensile Shear Test

Welding With Heat

Welding with heat involves the generation of heat by heating elements (e.g. cartridge heaters, heating foils) or by heat transfer through radiation. In order to achieve exact welding temperatures and to guarantee precise temperature distribution with larger components a complex system of temperature regulation is necessary.

Joining in the Mold

Thermoplastics offer the advantage of resoftening and welding, and this property is employed when joining components at appropriate pressures. Relatively high levels of dimensional accuracy can be obtained if a mold is used. One disadvantage, however, is that the parts to be welded must be heated up completely and not only at the welding areas. This requires relatively large amounts of energy and for thermoplastics with high cooling rates also a large expenditure for cooling. If the component has hollow spaces, supporting cores must be inserted since the entire component softens. In general, the process of joining in the mold renders good and reproducable values. The limitations of this process lie in the size of the component or that of the press, and the equipment required for energy production and regulation.

This technique was approved in the joining process of CF-PEEK (APC 2) parts. Other advantages are: fiber orientation is maintained, fibers are not damaged and small rough spots can be smoothened.

As an example, Fig. 11 shows a section of a stringer joined together from 3 parts in a mold.

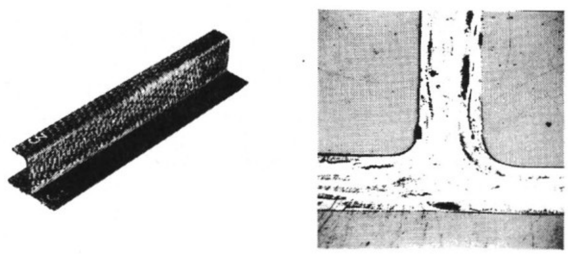


Fig. 11: Stringer Section

Listed below are the welding parameters used for CF-PEEK:

Mold temperature: 385-395 °C
Molding pressure: 5-10 bar
Joining time: depending on component thickness, 7 min per 1mm wall thickness, plus heating-up phase.

A mean value of 68.5 N/mm^2 was attained in the tensile shear test.

For further comparisons the samples welded in the mold were taken as standard value with 100 %.

Welding With a Heating Mirror

In order to avoid the heating of the entire component with fiber-reinforced thermoplastics, an electrically heated "mirror" was positioned between the surfaces to be welded. This heating mirror can be made according to the contour of the component concerned. For this process brackets are needed to clamp and position the parts to be welded. The joining zone is heated with contact or radiation heat. After obtaining the necessary plastification the heating mirror is removed and the parts are pressed together. There is no limitation as to the dimensions and the welding surface may be spherically curved, too.

Welding tests performed with CF-PEEK (APC 2) show Fig. 12 that - due to the high welding temperature of 390-400°C - the heat required should be transferred by contact. If the heat is transferred by radiation, the heating mirror must be brought to a considerably higher temperature (more than 500°C), depending on the distance. In addition, no release agent should be applied to the heating mirror. In the tests conducted, heating was achieved by direct contact since the heating mirror could only be heated to 400°C. Withdrawing the heating mirror did not cause any tearing of the matrix material and fibers.

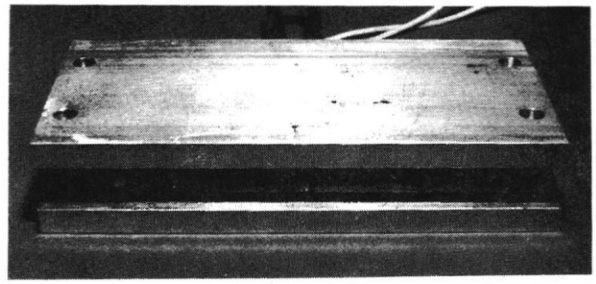


Fig. 12: Equipment for Weldung With Heating Mirror

Listed below are the welding parameters:

Welding surface: 90x130 mm^2
Heating mirror temperature: 400 °C
Soaking time at 400°C: 5 min
Initial pressure after removal of heating mirror: 5 bar
Pressure time: 5 min

Samples were tested with heating mirrors with and without a release agent applied.

The results from the samples tested are shown in Fig. 13. The effect of the release agent is clearly apparent. The shear strength value of the samples with release agent is 53.4 N/mm^2, that of the samples without release agent is 62.9 N/mm^2, which means 92 % of the reference samples. It is important that during welding appropriate pressure is applied to smoothen rough spots in the components, thus ensuring welding across the entire surface.

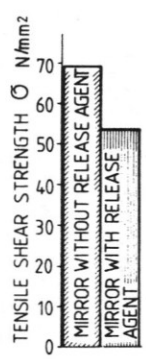


Fig. 13: Welding With Heating Mirror, Test Results

Welding With a Heating Element

The use of a heating element embedded in the joining surface provides the advantages of welding with a heating mirror, without the danger of damaging the welding surface by fiber and matrix-sticking. This heating element could have the form of a metal grid connected to the power supply which remains in the component, but this could have a negative effect on the properties.

At DFVLR work was done on a process not requiring the use of foreign materials. Particularly, in the case of CF-PEEK (APC 2) the good isolation properties of the matrix material and the good electric conductivity of the carbon fibers make it possible to produce a heating element which corresponds to the properties of the component's composite material and that enables the required electrical power to be produced.

Production of this type of heating element is performed as follows:

The matrix must be removed at the contact points in order to ensure a good transfer of current into the heating element. The following methods were studied:

- Mechanical removal by sandpaper
- Chemical removal by submersion in hot sulfuric acid for approx. 1 min
- Thermal removal by careful application of a Bunsen burner.

Resistance measurements were conducted on PEEK-impregnated carbonfiber rovings of different lengths subjected to the above procedures. The largest contact resistance was measured with the sanded current connections; chemical and thermal removal produced lower but comparable resistance values. Since thermal removal is easier to achieve, this process was chosen to produce the current connections.

On the whole, two types of heating elements were produced and tested in the study:

- Heating elements made of PEEK-impregnated carbonfiber rovings
- Heating elements made of APC 2 prepregs

Heating Elements Made of PEEK-Impregnated Carbonfiber Rovings

In order attain the maximum heating power, the roving was packed in a zigzag shape as tightly as possible on a metal plate fitted with steel pins. To bend the rovings around the pins a hot-air blower was applied to the PEEK matrix until it softened. Then the roving was pressed under heat between two plates to form a flat heating element, Fig. 14.

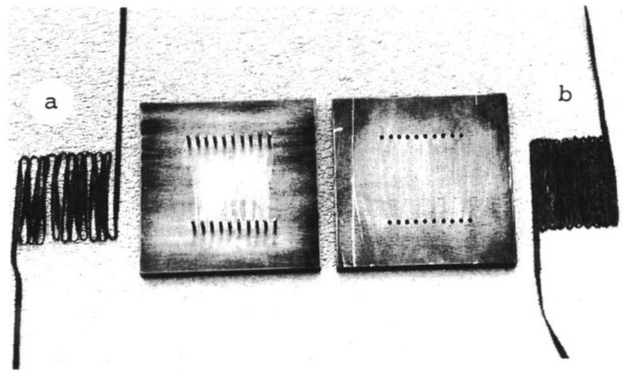


Fig. 14: Heating Element
Made of Impregnated Roving
a) After Winding
b) After Pressing

The loops of this type of heating element often displayed fiber tears caused by the concentration of fibers in the radii which could not be evened during pressing without fiber damage.

In a later procedure the heating element was produced by winding it over a metal core which was removed before the heating element was pressed. Thus it was possible to prevent the mentioned fiber damage. But here, too, as the temperature approached the matrix melting point, short-circuit currents occurred leading to local areas of overheating.

Heating Elements Made of APC 2 Prepreg

Heating elements made of APC 2 prepreg, Fig. 15, avoid the problems with the above mentioned heating elements, presumed that current is introduced in a very uniform manner.

In a series of preliminary studies it was shown that the best method for current introduction was via a metal terminal of the same width as the heating element, with carbon fiber fabric - fiber direction $\pm 45^{\circ}$ - applied between the metal clamp and the heating element. Temperature distribution was measured with a temperature sensor at 16 points on a heating element (50 mm wide, 130 mm long) exposed to a free air environment under the following conditions:

Constant voltage 13 V,
current intensity 15 A.

The temperature distribution can be assumed as uniform and ranged between $171^{\circ}C$ and $178^{\circ}C$.

The test set-up is shown in Fig. 16. Each time two APC 2 plates ($130 \times 50\ mm^2$) with a thickness of approx. 2 mm were welded.

Fig. 15: Heating Element
Made of APC 2 Prepreg

An unreinforced PEEK foil serving as welding foil was placed between the heating element and the APC 2 plates. The temperature curve was measured and recorded with an embedded thermocouple, electrically isolated by Kapton foil. Current was introduced into the heating element via thermally stripped ends and metal clamps. Between heating element and clamp a layer of $\pm 45^{\circ}$ carbon-fiber fabric - cut carbon-fiber fabric hose - was used.

Electric current was supplied by a transformer and manual voltage control.

To minimize heat loss and required heating power, the supports and the press were thermally isolated by cellular concrete plates of 5 cm thickness.

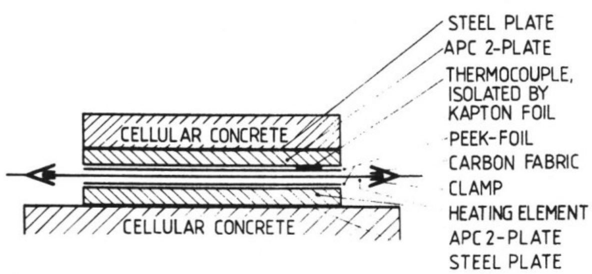


Fig. 16: Heating Element,
Schematic Test Set-Up

Evaluation of the samples subjected to the tensile shear test showed that the strength of the samples was dependent on bonding pressure during welding: at no pressure 12.4 N/mm^2 was attained, 33.3 N/mm^2 at 1 bar and 65.6 N/mm^2 at 5 bar, Fig. 17.

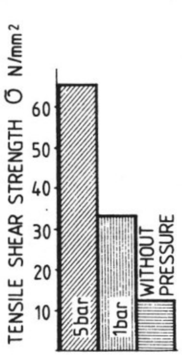


Fig. 17: Welding With
Heating Element,
Test Results

The value at 5 bar corresponds to 96 % of the reference sample.

Welding with Friction

The usual welding processes:

- Ultrasonic welding
- Vibration welding
- Rotation welding

all employ the principle of heat produced by friction. Introduction of required energy is achieved in different ways. The processes are described in the following sections. Application is guided by the size of the components and their design. It is necessary to exactly determine the appropriate welding parameters since the matrix material, fiber content and fiber length have a major effect on all processes.

Ultrasonic Welding

In ultrasonic welding facilities high frequency electric vibrational energy - supplied by a generator - is converted into mechanical energy by an ultrasonic converter. Transfer to the plastic part to be welded is performed via a transforming element (booster) and the welding tool (sonotrode), Fig. 18. The generator and ultrasonic converter act in resonance with booster and sonotrode. The energy introduced is converted via molecular and interfacial friction into the heat required for fusion. The thermoplastic parts fuse at the contact areas and become bonded.

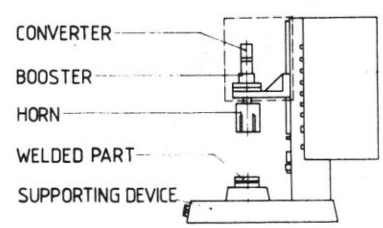


Fig. 18: Ultrasonic Welding, Schematic

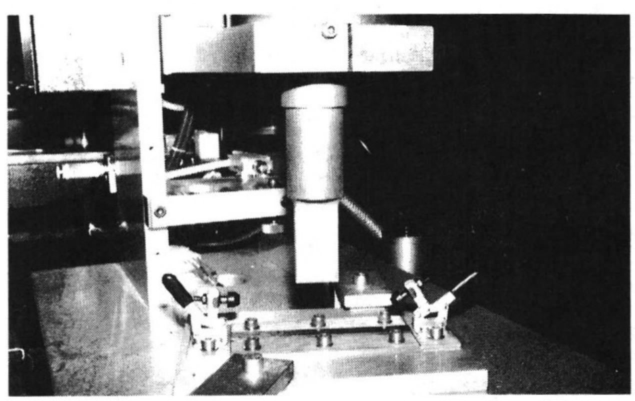


Fig. 19: Ultrasonic Welding, Equipment

To gain proper and reproducible values it is important to have a welding area with energy flow direction sensor and to optimize the welding parameters. One aspect for design and selection of the sonotrode includes the specification of small contact areas in order to achieve a high level of energy concentration.

Continuous fiber-reinforced thermoplastics can be welded ultrasonically. The design of the energy flow direction sensors - for unreinforced or short fiber-reinforced thermoplastics conical or knop-shaped - is impossible since this results in fiber damage. For the tests on continuous fiber-reinforced CF-PEEK (APC 2), prepreg strips in longitudinal direction, PEEK foil and PEEK powder were used as energy flow direction sensors. The results show that all three types are possible. Uniform application of the powder is problematic and the prepreg strips should be as wide as the welding area, with the fiber orientation longitudinal to the welding area. Tests show that welding was impossible when both parts were clamped with a bracket. This means that if the distance between in welding points is too small, for example when welding a stringer, the quality of the weld can be impaired. Listed below are the parameters under which welding took place:

Test series	Nr 1	Nr 2	Nr 3
Sonotrode size (mm):	36x15	76x12.7	38.0ø
Welding area (mm^2):	420	912	456
Welding time (sec):	1.0	to	2.0
Amplitude (mm):	70	56	75
Holding time (sec):	2.0	0.5	1.0
Holding pressure (on sample) (bar):	26	8.2	11.3
Power (Watt/cm^2):	100	to	373

Figs. 20 and 21, are presented for test series Nr. 3. Evaluation of these graphs show that several welds broke off prior to the prescribed time before welding was completed while other samples with the same parameters exhibit perfect welds. One reason could be due to the energy flow direction sensors; varying thicknesses or fiber contents of the prepreg result in changed parameters which cannot be compensated by automatic adjustment.

The results of the tensile shear tests, Fig. 22, show a decrease in tensile shear strength with increasing power, due to damages of the welding area.

Ultrasonic tests showed that the welding quality varies over the entire joining surface. Compared to the samples welded in the mold, the shear stress values for optimum welding power (for our samples 100 W/cm^2) correspond to 58 % of the shear stress of the reference samples.

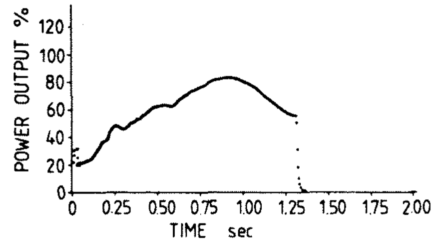


Fig. 20: Ultrasonic Welding, Automatic Break Off

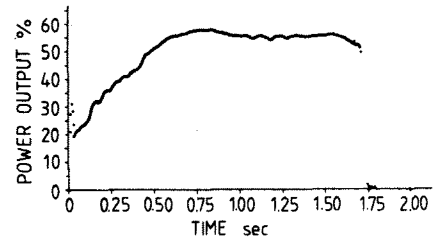


Fig. 21: Ultrasonic Welding, Full Welding

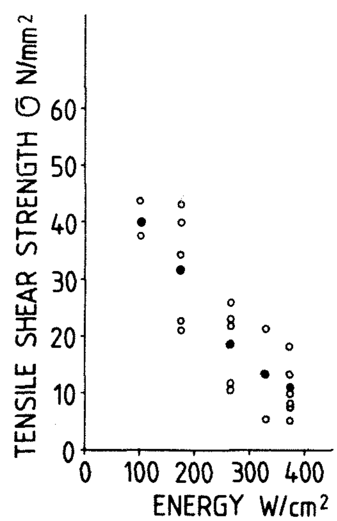


Fig. 22: Ultrasonic Welding, Test Results
o Single Value
● Mean Value

Ultrasonic Spot Welding

Spot welding is a common method of welding thermoplastic parts with large areas. Tests have shown that this process is not suitable for components made of CF-PEEK (APC 2); the sonotrode made of titanium melted after a few number of tests, Fig. 23. The fibers in the centre area were also separated, Fig. 24.

Fig. 23: Ultrasonic Spot Welding,
Sonotrode After 3 Weldings

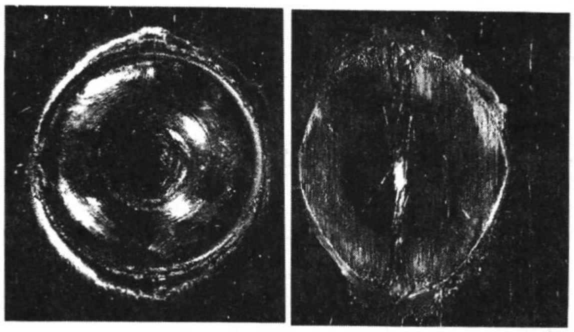


Fig. 24: Ultrasonic Spot Welded Samples

The few usable spot-welded samples (3) were tested analagously to the sample form of the other welding methods, with the distance between the notches changed. The distance was chosen such that the welding point (diameter = 8 mm) was positioned between the notches, thus, that the entire welding surface (50.3 mm^2) could be tested. The failure load for the samples subjected to the tensile shear test was 862 N in the first welding test (undamaged sonotrode) and for both further tests 594 N and 648 N. By comparing these results with the values expected from an ultrasonically welded point of the same size under optimum conditions, these values are too poor to continue tests by this method with various sonotrode materials.

Vibration Welding

Vibration welding is a linear friction welding process. The required plastification is achieved by pressure and forced friction in the joining zone. For the welding process one part is held in fixed position to the lower jig. The lower jig is permanently attached to the lifting table mounted on vertical columns and cannot move horizontally. The second part is clamped into a holder on the vibrating head and vibrates according to the set amplitude, Fig. 25. The end of the welding process can be controlled as a function of travel or time. After welding is completed, the machine switches from welding pressure to a preset post-weld holding pressure.

Energy conversion takes place at the location where it is needed and thus an additional supply of heat is not necessary. The welding time is a matter of seconds. Energy flow direction sensors are not needed.

In contrast to ultrasonic welding, larger joining areas and a larger number of thermoplastics can be welded. The outer form of the components can be irregular, they only must be held securely in fixed position. However, one prerequisite is that the joining seam allows a straight frictional movement along one axis.

To investigate the applicability of continuous fiber-reinforced CF-PEEK (APC 2), strips 130 x 12 mm^2. Were cut from a pressed plate and welded, Fig. 26. The tests showed that - in contrast to ultrasonic welding - the entire sample surface was welded. When setting the welding parameters, the welding time was increased until the sample showed uniform material discharge (fibers pressed out with matrix), that is until the sample was uniformly fused at all points. When the welding time was shorter (dependent on pressure) the sample was welded only at those points which had better contact to the backing. The tolerances here were in the 1/10 mm range. Ultrasonic pictures showed the same echo over the entire welded area, thus indicating uniform welding.

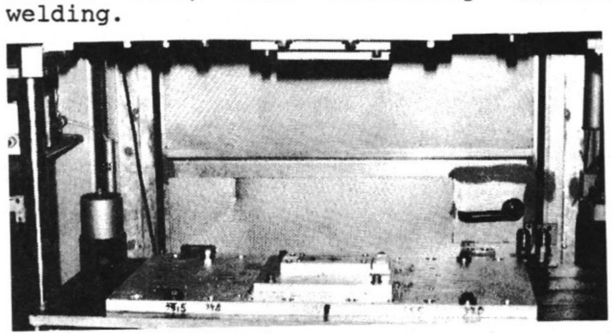


Fig. 25: Vibration Welding Equipment

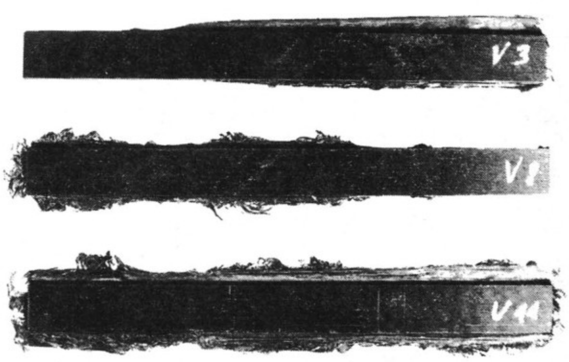


Fig. 26: Vibration Welded Samples

The technical data were:

Welding time: 4.5-8.0 sec
Holding time: 2.0 sec
Welding pressure: 33 or 18 bar
Holding pressure: 33 or 18 bar
Vibration amplitude
at a frequency of 240 Hz: 1.7 mm

The results of the tensile shear test, Fig. 27, are good, with a shear stress average value of 49.7 N/mm^2 i.e. 73 % of the reference value, especially in view of the fact that welding took place over the entire surface and not only at certain points. The large scatter of values (35 to 58 N/mm^2) is unsatisfactory; however, the mean value could be raised to more than 50 N/mm^2 by optimizing the welding parameters.

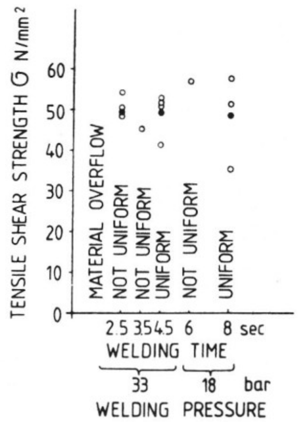


Fig. 27: Vibration Welding, Test Results

Remeasuring of the samples revealed different end thicknesses for an identical initial thickness of 4.6 mm. Uniform material discharge and identical sample thicknesses were attained with the following parameters:

Welding pressure: 33 bar, 18 bar
Holding pressure: 33 bar, 18 bar
Welding time: 4.5 sec, 8.0 sec
Holding time: 2.0 sec, 2.0 sec
Sample thickness: 4.08mm, 4.32mm
Thickness tolerance .15mm, .10mm
between samples:

Rotation Welding

Rotation welding is a type of friction welding. This process is suitable for bonding rotationally symmetrical formed parts. One part rotates and the second part is held in place. After rotation is stopped the weld "freezes".

Plastification is achieved at a preselected rotational speed in the first pressure stage, with the torque held constant. This pressure range is set up so that plastification can be achieved with a low contact force, if desired. When fusion is achieved pressure can be raised to the second stage.

In general the distinction is made between, Fig. 28:

- Circular surface welds,
- Ring-shaped surface welds, and
- Conical surface welds

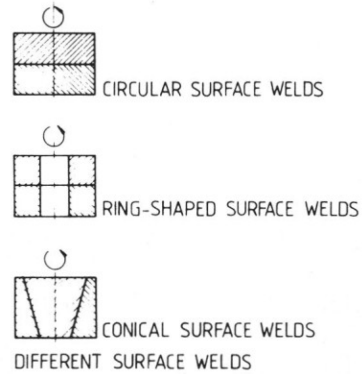


Fig. 28: Rotation Welding, Different Surface Welds

Possible applications for rotational friction welding in processing CF-PEEK were studied using winded type pieces - wall thickness 2 mm - made of APC 2. A conical surface weld was chosen to maintain the favourable properties of continuous reinforcement. The cone had an angle of 7°. The study showed that it was necessary to clamp both tubular pieces and that the welding point had to be supported not only on the inside by a centering mandrel but also on the outside, Fig. 29.

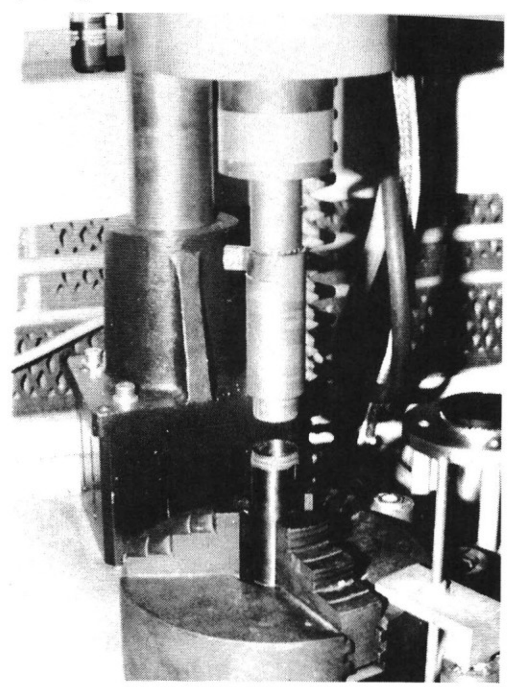


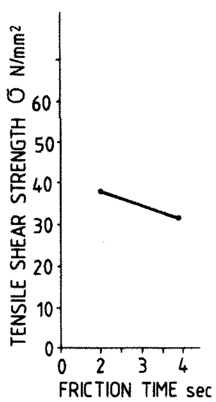
Fig. 29: Rotation Welding Equipment

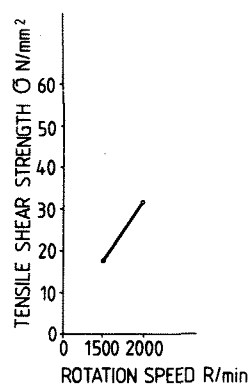
The technical data were as follows:

Rotational speed:	2000	2000	1500	R/min
Friction time:	4.0	2.5	4.0	sec
Holding time:	10	10	10	sec
Frictional pressure:	2	2	2	bar
Post-weld holding pressure:	2	2	2	bar

In order to determine the welding quality, the welded tubular piece was cut into 12 mm wide strips and subjected to a tensile test.

Figs. 30, 31 show that rotational speed and friction time have an important effect. Maximum shear stress values had a mean value of 38 N/mm^2. The reference sample with the same layer construction, cut from a pipe which had not been welded, had a value of 167 N/mm^2.





Rotation Welding

Fig. 30: Influence of Friction Time

Fig. 31: Influence of Rotation Speed

An analysis of the results shows that it is very important to optimize the parameters. In addition, it could be seen that with all welded samples approximately only one third of the welding surface was actually welded. One possible reason is that after the tube with a thickness of only 1.25 mm was processed, the conical surface had become slightly ball-shaped, thus preventing uniform contact at all points of the surface to be welded.

Though the shear stress values of the samples produced by the rotation welding method attained only 22.7 % of the reference sample, they could attain considerably higher values with an appropriate optimization of the process and a more exact preparation of the samples.

Induction Welding

The EMAWELD process /3/ is a type of induction welding. In this process a welding aid made of EMAWELD material with an application of magnetically activatable powder is positioned between the two components to be joined. The powder particles are embedded in the same or in a similar thermoplastic from which the components are made. A high-frequency magnetic field causes the particles to be heated through hysteresis and eddycurrent losses, raising the welding aid to melting temperature and thus producing a weld.

The advantage of the induction welding technique is that heat energy arrives at the surfaces to be joined quickly and without loss.

In this process, as with other processes, the design of the weld is decisive for its quality. The induction welding process is, according to the manufacturer, suitable for welding of large parts up to 6000 mm in length and can also achieve continuous and three-dimensional welding lines.

Long and multiple welds must be performed in one operation. For fiber reinforcements with a high fiber content, the thermoplastic welding aid is suitable to supply necessary additional matrix material.

Welding PEEK with the EMAWELD process is still in the experimental stage. Welding tests using plates produced by DFVLR (for 2 welding tests) and made of CF-PEEK (APC 2) were conducted by Emabond Incorporated. Tensile shear samples from the first welding test, which also displayed faults, showed values between 16.0 and 29.6 N/mm^2. The samples from the second welding test (perfectly in appearance) produced a mean shear stress value of 54.7 N/mm^2. This corresponds to 80 % of the reference sample and is a good value.

Joining Thermoplastics with Adhesives

Another method of bonding thermoplastics is by adhesives.

Based on the manufacturer's recommendation, tests were conducted with the adhesive:

FM 300 (Cyanamid)

along with the following adhesives:

Araldit AV 119 (Ciba Geigy)
Agomet F 310 (Agomet Adhesives)
Agomet F 330 (Agomet Adhesives)

Pretreatment of the samples was performed as follows:

- Degreasing
- Slight roughening of adhesive surface
- Cleaning
- Thin application of adhesive

Special activation of the area to be joined was not performed.

The adhesive was cured according to appropriate manufacturer's instructions.

The bonded CF-PEEK plates were cut in accordance to the sample shape shown in Fig. 10, and the notches were milled. The adhesive on all samples bonded with Araldit AV 119 or Agomet F 310 separated during this processing or when the samples were clamped into the loading device.

Only one sample from those bonded with Agomet F 330 (6) withstood the processing. The shear stress value was calculated to be 4.2 N/mm^2. From the samples bonded with the adhesive FM 300, 4 out of 7 samples withstood processing. The mean value of 12.6 N/mm^2 corresponds to 18.5 % of the reference value and is the poorest value from all of the joining techniques.

The only advantage of using the adhesive technique is its easy handling and the fact that fiber damage on the joining surface can be prevented.

Comparison of Different Bonding Techniques

For comparing the different joining techniques they must be subdivided into processes, Fig. 32:

- which weld entire surfaces
- which only perform spot welding
- which can damage the interface.

The results are shown in Fig. 33. The best results are obtained with those methods which employ heat (mold, heating mirror, heating element and the EMAWELD process). With these welding methods fiber orientation and wall thickness of the components are retained.

The application of methods which weld by friction is possible, however, entail lower shear stress values and require a higher level of expense to effect optimization. The fiber orientation at the interface does not remain unchanged, the fibers shift partly together with the matrix material; this means that the wall thickness changes slightly. The best results with this welding category can be obtained with vibration welding. Ultrasonic welding is only applicable to a limited extent, due to the necessity of using energy flow direction sensors, and the relatively small welding surface.

Adhesive bonding with PEEK is problematic. For those samples which withstood

	BONDED AREA: NOT DAMAGED	BONDED AREA: DAMAGED
AREA-BONDING	MOLD HEATING MIRROR HEATING ELEMENT INDUCTION ADHESIVE	VIBRATION ROTATION – – –
SPOT-BONDING	–	ULTRASONIC

Fig. 32: Bonding Techniques, Influence on Bonding Area

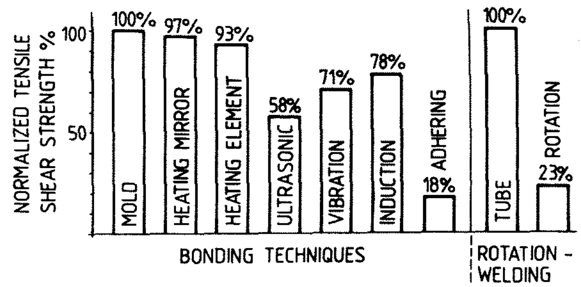


Fig. 33: Comparison of Different Bonding Techniques, Test Results

the processing, the shear stress values were poor. Using adhesives only can be considered when large joining surfaces are involved.

Welding tests with hot gas and laser were not dealt with in this report. The tests with hot gas were stopped because the results were not satisfactory (oxidation of the matrix due to excessively high gas temperature and strength values too low). An appropriate laser was not available.

Acknowledgement

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