Deutscher Luft- und Raumfahrtkongress 2010
DocumentID: 161157

REPAIR CONCEPTS FOR CARBON FIBRE REINFORCED THERMOPLASTICS

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ABSTRACT

In addition to fibre reinforced composites based on thermoset matrix systems, fibre reinforced high-performance thermoplastics are continuously gaining market share during last years, especially for primary and supporting parts in planes. They show a high achievement potential and advantages in comparison to thermosets. After the first moulding process, thermoplastic matrix fibre composite parts can be reshaped or welded. To accomplish general acceptance, it has to be shown, that repair is possible to the points of failures or defective areas without big expenses, and without any significant reduction of mechanical strength. Due to these properties, new repair concepts for thermoplastic parts and structures had to be developed.

During the last years, different welding technologies have been analysed and developed at the German Aerospace Centre (DLR), Institute of Structures and Design. Especially the resistance implant welding technology using carbon fibre reinforced Polyetheretherketone (CF/ PEEK) was one of the area of main interest. Regarding repair needs, the aim of this technique is to ensure the joining between the patch and the detective laminate.

In addition to the summary of research using resistance implant welding technology, the possibility to simplify the repair process using laser support and optimization of the stepped-lap joining are also presented. First results have shown that mechanical machining of composites using a laser system is possible. Furthermore, the steps can be manufactured precisely and without any damage of the material.

1. INTRODUCTION

A repair technique has to be applicable, reliable and cost-effective. Any damage on the structure around the repaired area should be avoided. The aim of this project is to develop a repair concept for fibre reinforced thermoplastics with the above mentioned characteristics and a proven procedure to repair primary structures. Main focus of the repair is to recover the mechanical integrity and the aerodynamical shape. The repair has to ensure that the repaired parts will not lose their function to resist the design loads, whereby the force allocation will not change.

Compared to parts made of fibre reinforced thermoset materials, a bonded repair is suitable to only a limited extent for this type of matrix materials, and for this reason it is not within the main focus of this project. An alternative has to be found to prepare the area of repair and afterwards close the area of repair permanently with a patch.

All investigations this paper is based on establish a basis for different techniques like the resistance welding or manufacturing of machining using a laser-system. The possibility to integrate some of these techniques into a repair concept has been studied.

As an example for the repair concepts, the slat of an airliner will be observed. In addition to torsion and bending loads, the slat is also under threat of impact by foreign objects, especially by bird-impact. To ensure that the repair is able to bear the loads, a stepped-lap joining between patch and the structure around was chosen.

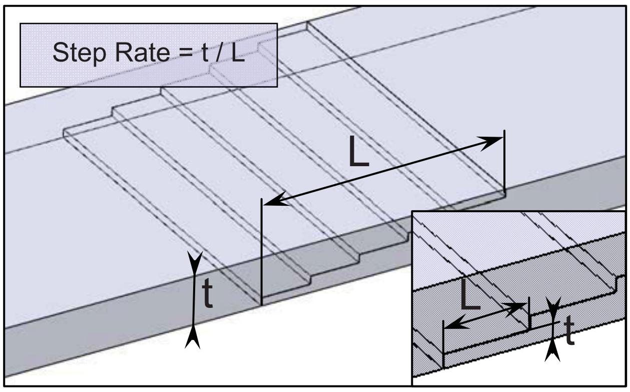

FIGURE 1: Calculation of the step rate

Other investigations show that the highest stresses can be achieved with this kind of joining [1]. In FIGURE 1 a stepped join is illustrated.

In comparison to other repairing processes (e.g.: outer and inner patch; bonded and/or fixed with bolts), the joining of the several plies can be recovered to a certain extent with the help of a stepped joining.

The repair process includes several steps. After the localization of the failure, an applicable non-destructive-testing method (NDT) has to assess the degree of the damage.

Next step is to remove the defected material via applicable procedures. The structure of the repair depends on the damaged area and may have a complex 3-dimensional geometry. Regarding these requirements, manually scarfed removals (inaccuracy, poor quality) as well as scarfed removals by chamfer (insert thermal stresses) are less suitable for this process. To solve this problem, the application of an UV-laser-system has been studied within this project. Results, concerning quality and accuracy of the machining, will also be presented and discussed.

2. RESIDUAL STRENGTH BASED ON SPECIMENS

For the manufacturing of larger and minor vaulted thermoplastic structures, the vacuum consolidation technique (VCT) was developed in the 80' at DLR, Institute of Structures and Design. The VCT is a cost-effective and high-quality processing technology, which can produce consolidated laminates of repeatable quality [3]. Only the compressive force of the vacuum is necessary to compact the material. Cost-intensive equipment, like an autoclave or a heated press, is not required.

The vacuum consolidation technology is based on a simple heated metallic plate, concurrently representing the lower half of a heated mould. Due to the high crystal melting temperature of the material investigated here (343°C for PEEK), the supporting utilities, like vacuum bag, sealing tape, fleeces, insulating materials etc. must be thermally resistant to high temperatures. A foil on top of the stacked lay-up provides the upper mould in combination with its function as vacuum bagging. The consolidation process itself is characterized by heating up the laminate under vacuum conditions. Obviously, the geometry of the heated plate is not forced to be flat. Complex 3-D shapes are feasible as well. The principle of this technique is shown in FIGURE 2.

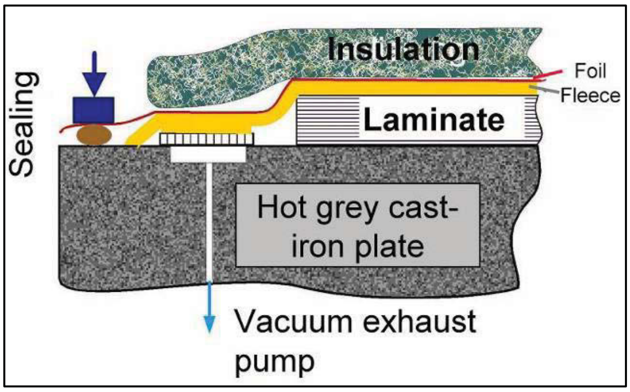

FIGURE 2: Typical build up for a vacuum consolidation

Before consolidation, each single ply has to be cut through its fibre orientation according to the ply-book. This can be done easily by an automatic cutting system as well as by the laser system itself. Next step is the stacking of all plies together, here realised by using an ultrasonic pistol. Afterwards, the stacked plies must be positioned on the heated plate and coped with thermal resistant foil. Mostly glass fibre mats are used as an additional layer to insulate the laminate. After reaching the processing temperature, temperature has to be kept constant in order to complete the consolidation.

Within first investigations, different specimen geometries were chosen. The thickness of the specimen plates had been 4,6mm resp. 2,3mm. The plates had been of a quasi-isotopic resp. unidirectional lay-up with 32 resp. 16 single plies. All specimens were manufactured from unidirectional CF-PEEK tapes supported by the company Toho Tenax Europe. The P-Yarn fibres of Toho Tenax are fitted with an optimized sizing for thermoplastic matrix materials, here in combination with VESTAKEEP 2000 of EVONIK Industries.

2.1. Laser as a tool for laminate repair

Quality and resolution of the manufacturing process strongly depends on the used laser source, pulse duration, frequency and the quality of the laser optic. Using a 355nm UV-laser system, the layer removal on CF-PEEK was experimented to determine the efficiency of the laser technique.

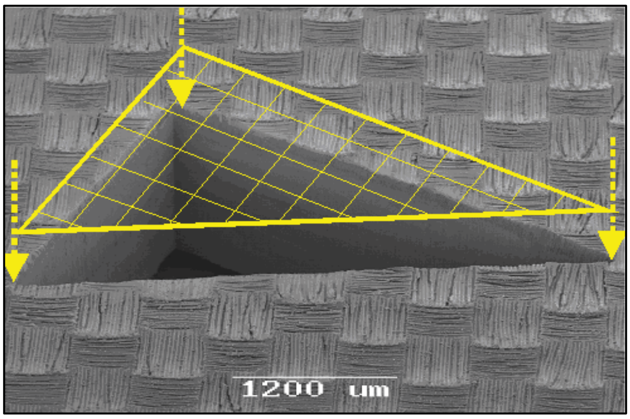

FIGURE 3: Ablation principle of the laser-machining

The low average beam power (23W) is transformed to pulse peck intensity in the GW/cm² regime by the ns-pulse duration with a repetition rate of up to 300 kHz. The laser beam is guided by mirrors into a galvometer driven scanner unit, which allows a highly dynamic beam deflection of over 3,0m/s. The ablation of a layer is done by hatching the area with parallel laser lines as shown in FIGURE 3 [2]. In order to flatten the ablated surface, the hatching direction was alternated 0°-90° for every couple of layers thus neglecting the influence of fibres direction on the depth of the cavity. Several cycles, with a depth per cycle ranging from 1µm to 25µm, can grind every ply precisely. The average thickness of a single ply of the used material is 0,125mm. Ply-to-ply of a CF-PEEK laminate can be removed without any thermal damages or delamination, with the help of described laser-system. This technique can be applied to any geometry of the scarf resp. steps.

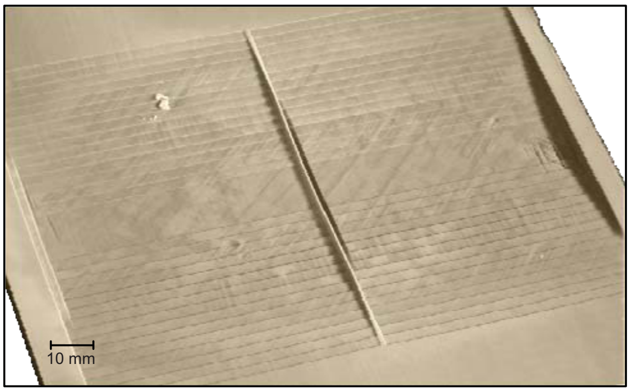

FIGURE 4: micro computed tomography of the grinding

To estimate the quality of the manufactured steps, some plates were examined with a micro computed tomography (µCT). With the help of the CT-picture in FIGURE 4, the steady-going grinding and the non frayed fibres at the edge of a step were detected. Additionally, the height of the steps was determined precisely, which were identical with the ply thickness.

FIGURE 5 shows the geometry of the steps in detail. Additionally, no thermal damage could be detected visually and by polished specimens. In case of hot ablation, a gleaming surface would remain on the matrix material.

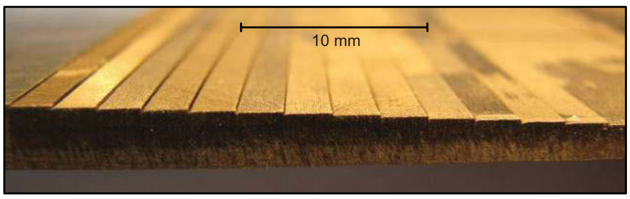

FIGURE 5: edge of the steps treated by the laser-system

Until now, every work regarding the grinding by a laser-system had been made by the Laser Zentrum Hannover e.V. (LZH).

2.2. Repair

Typical scarf angles from 1:20 to 1:50 are used for bonded repairs [1]. One reason to minimise the scarf angle is to ensure the repairing of the bended structures, nevertheless to meet the stiffness and strength requirements. Additionally, the area to repair will be smaller. For this reason, the investigations started with a scarf angle of 1:20. To be able to make a comparison, additional scarf angles of 1:10 and smaller will also be investigated. The manufacturing and also the repair process of the specimen plates are followed by the vacuum consolidation technique (VCT). 10 plates (each plate 4 specimens) with a quasi isotropic lay-up were manufactured for the treatment by the laser-system. Regarding the repair of these plates, all single plies of the patch were cut with particular sizes and fibre orientation [4]. After this, the plies were fixed and stabled in the grinded plate with the help of an ultrasonic pistol supported by BRANSON Ultraschall. This step of the repair process is illustrated in FIGURE 6 for a plate with a step-rate of 1:20. Next step is to integrate the patch in the plate by VCT. For these specimens, the Patch and the laminate were melted. During melting process, the patch and the laminate are jointed.

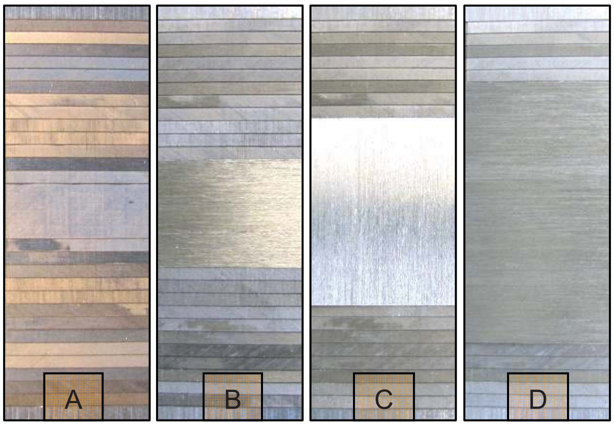

FIGURE 6: Repair process – stacking of the single plies

Picture A shows the result of the grinding by the laser. The other pictures (B-D) show the attaching resp. fixing of the single plies for the patch.

Unidirectional plates, which are used for the tension tests, were manufactured by a similar process. To simulate a repair, all single plies were cut at different positions, which changed from ply to ply depending on the step-rate and the overlap. Afterwards, the single UD-tapes were fixed and stabled with the ultrasonic pistol and consolidated by VCT. This step is similar to the repairing process of the laser treated quasi isotropic plates.

2.3. Test program und results

2.3.1. Interlaminar tensile testing - DIN 65148

During first investigations, interlaminare tensile shear strength of the laminates was measured according to DIN 65148. The results were evaluated and compared with reference specimens. FIGURE 7 shows the geometry of the specimen, with the two grooving located in the repaired area.

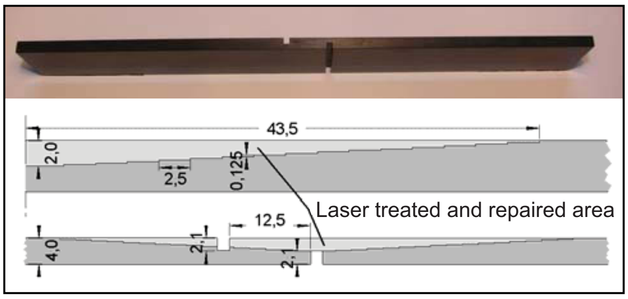

FIGURE 7: Specimen geometry and position of the laser treated repair area

According to the usual and current repair process, the examination started with a step rate of 1:20 (10 specimens) and continued with 1:10 (8 specimens). To be able to make a comparison, 20 reference specimens, which were not treated by laser, were additionally tested.

The analyses have shown no difference between the repaired and the reference specimens regarding the interlaminare tensile shear strength (FIGURE 8). That applied for both types of the repaired specimens, with a step rate of 1:20 and of 1:10. The average strength values of all specimens are in a range between 50 MPa and 60 MPa. This leads to the conclusion that either the step rate of the repaired specimens have no negative effect on the interlaminare tensile shear strength or the failure does not occur in stepped-lap joining.

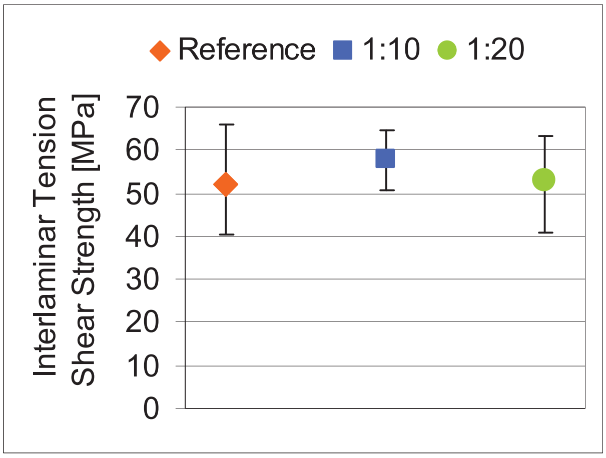

FIGURE 8: Strength of different step rates in comparison with strength of reference specimens

To be able to reach the exact conclusion, examination of the point of fracture was additionally carried out. In FIGURE 9, the point of fracture of a 1:20 specimen is compared with a reference specimen. As can be seen, in case of the 1:20 specimen, fracture appears within the interface of the patch (light gray) and the parental laminate (see FIGURE 7). In the reference specimens, the point of fracture was always located in the single 0° layer in the plane of symmetry. This proved that the failure occurred indeed within the stepped joining (area of repair), and that interlaminare tensile-shear strength of the repaired specimens with the different step rates does not decrease.

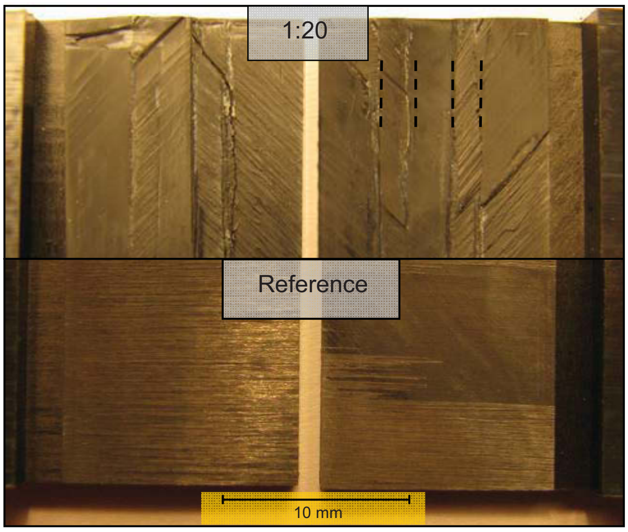

FIGURE 9: Fracture comparison of a stepped-lap and a reference specimen

2.3.2. Tensile testing – DIN 2561

In addition to interlaminare tensile shear strength, also tension tests were carried out to determine the tension-shear strength of the stepped-lap joining, as the tension-shear strength of the repaired specimens can also be defined as the residual strength. With the help of this specific value, the tension strength of conventional tensile specimens can be compared with the residual strength of the repair. The specimens were tested according to DIN 2561 (unidirectional laminates, tensile test parallel to the fibre direction).

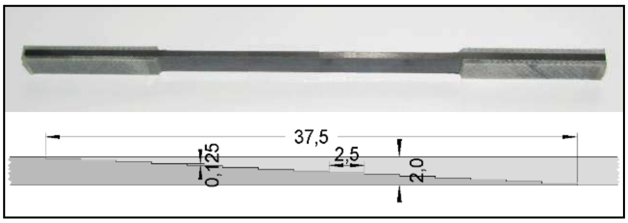

FIGURE 10: Specimen geometry and repaired area to measure the residual strength

The geometry and the illustrated repair are shown in FIGURE 10. First of all, repaired specimens with a

step rate of 1:20 had been tested. To optimize the consolidation within the repair process, several tests were carried out. In FIGURE 11 the fracture of two different specimens from the beginning of the investigation (lower picture) and of the latest state (upper picture) are compared. The optimization quadrupled the residual strength of the repair.
This could be achieved by avoiding failure in the fibre matrix interface. Optical analysis and a comparison between the two specimens support the idea that the failure occurred in the pure matrix. To prove this thesis, the analysis will be accomplished by a high-resolution microscope and SEM in the course of investigations. With the help of fracture analysis, the type of failure could be better assessed.

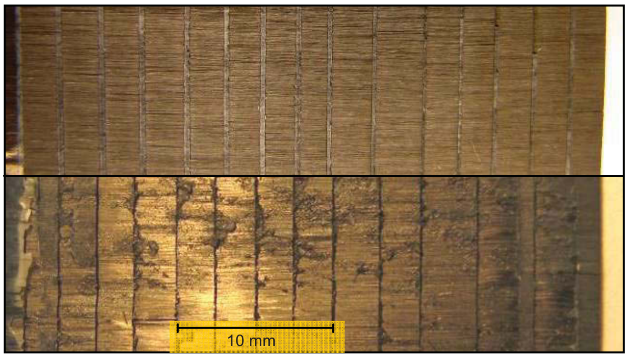

FIGURE 11: Changing of the fracture during the course of the investigation

The failure, which is caused by shear and the cut in each single ply, happened between the overlapped plies. In this scenario, repair has decreased the average tensile strength about 48% and the stiffness about 40%, compared to material properties.

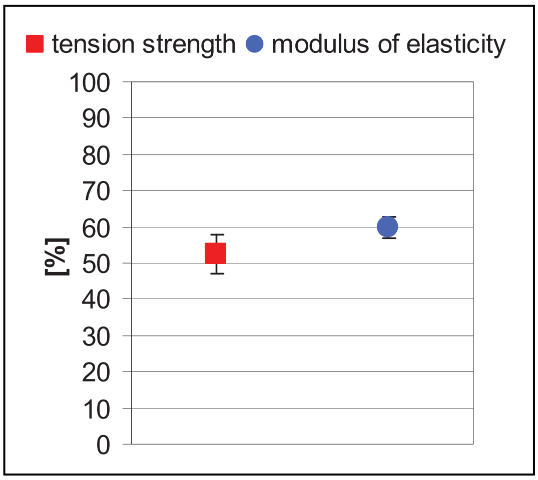

FIGURE 12: Residual strength of the repaired specimens with a step rate of 1:20

In 100% mark in FIGURE 12 is comparable to 2200MPa for tension strength and 132GPa for modulus of elasticity. These values had been measured by non defected reference specimens. The results additionally showed that the difference between the measured strengths and the average value is very low, what means a very good repeatability. This aspect is essential for a repair process.

2.3.3. Resume of the test result

The results of the previous investigations have shown that the establishing of high-quality, exact grindings with different step rates and geometries are possible with the help of the laser technology. These investigations confine to steps with a height of one single ply. Additionally it was proven that the interlaminare tension-shear strength of repaired specimens by this kind of grinding shows no decrease.

A comparison between the tensile strength and the residual strength of the laminates showed that repair with a step rate of 1:20 can recover the static strength about 50 % and the stiffness about 60%. The results of the residual strength were similar to the results of comparable investigations with a thermoset matrix. However, this process has a significant higher expenditure on repair because of additional inner and outer patches [5].

Further investigations should verify the effect of the fibre matrix interaction and the influence of shear strength on the residual strength of the repair. Based on these characteristic values, an analytical model will be generated. Furthermore, investigations regarding additional step rates, the effects of contamination, temperature and moisture and also dynamic tests will be carried out.

3. HEAT GENERATION WITHIN INTERFACE ZONE

For realisation of thermoplastic repair, the interface zone of the repair area has to be heated up to consolidation temperature. For first examinations in laboratory, heating up of the entire specimen is a simple way. As in this case stiffness of the entire structure is reduced, supporting of the structure is needed. If possible, therefore a heated tooling should be used.

The described VCT is suitable for part manufacturing. An additional tool needs to be developed, or VCT adapted, to be able to repair fibre reinforced thermoplastics, for both, in-shop and in-field repair scenarios. This tool must be transportable and adaptable to different, in many cases curved structures. For the joining between the patch and the defective laminate, some welding processes provide an alternative to the VCT. Regarding the last years, a number of studies about the resistance implant welding were carried out at DLR, Institute of Structures and Design. These studies form the basis for further investigations regarding repair concepts. In the following, several procedures are presented which can be used as a tool for the repair concept.

The results, which were made at the institute about resistance welding, are summarised in chapter 3.4.

When looking on a real structural component, accessibility from the back is limited due to additional structures like stringers and/or ribs. Due to these boundary conditions and the need for application of the consolidation pressure from the outer surface, possible set-ups for heat generation are limited. When looking on thermoset matrix material, integrity of the structure is in about the same range at temperatures below decomposition temperature. So, additional support is not necessary [6].

3.1. External heat sources

The most commonly known technique for applying heat in case of repair of thermoset matrix material is the use of external heat sources like UV-heaters or heated mats. As curing temperature of thermoset matrix material is far below processing temperature of high-performance thermoplastic matrix material, convective heat transfer can easily be used for these materials. Heat conduction of the carbon fibres and, due to this, inhomogeneous temperature distribution might lead to incomplete consolidation of thermoplastic materials. On the other hand, when talking about thermoset materials, conductive heating of the interface area is the most suitable process.

3.2. Volumetric heat generation

An interesting variant of implementation of heat is the volumetric heat generation, which is examined in some research institutes [9, 10, 11]. In this case, the combination of matrix and suitable fillers or nanotubes leads to an interaction with an electromagnetic field. As a result, neat matrix material can easily be heated up, local or within the entire volume, by induction.

Even in combination with non-conductive fibres, e.g. glass fibres, homogeneous heating up can be realised. When dealing with conductive fibres, e.g. carbon fibres, normally used in aircraft structures, due to interaction with the electromagnetic field temperature gradients and/or local hot spots may occur [13]. Depending on the maximum temperature, the composite might be damaged by these effects.

3.3. Inductive heat generation

Varying from the before-mentioned process, another possibility of locally generating heat in combination with electromagnetic fields is the usage of so-called inductors. Susceptors, in general based on stainless steel meshes with mesh size optimised for the wavelength, are transforming electromagnetic field energy into heat energy. Inductors are commonly used in induction welding and remain within the welded structure.

When using this method, it is possible to generate heat in a defined layer, but interaction of electromagnetic field and conductive carbon fibres can not be avoided. This effect is limiting the potential of this technique, especially in combination with high-performance thermoplastic material.

3.4. Electrical heat generation

The most simple technique for joining fibre reinforced thermoplastic materials is the electrical heating up of a resistive element, the resistant implant welding technique. This technique uses a resistive element which is trapped between the parts to be joined; homogeneous heating up is realized by applying a current. Within this technique, the usage of resistive fibres is possible in addition to conventional, metal based resistive elements. When using carbon fibre based elements, there would be no different material remaining in the structure.

As can be seen in FIGURE 13, welding setup is quite simple. Control of the welding process normally is realised by monitoring the electrical parameters, welding pressure and process time. Investigations at DLR, Institute of Structures and Design are focused on the substitution of metallic heating elements by carbon fibre based elements, whereby in this case the use of unidirectional fibres is of interest as well as the use of fabrics.

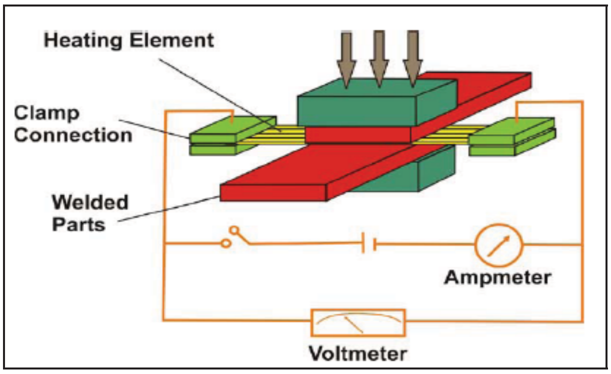

FIGURE 13: Scheme of a welding setup [14]

One of the focal demands for resistive elements is the resistance of the element in relation to temperature of the element. For optimal and repeatable results, this quotient should be constant over temperature and time. At the same time, the thickness of the welding element should be minimised due to impact on mechanical properties of the joint area.

On the other hand, thickness (which has an impact on resistance) might be of great interest regarding reproducibility when dealing with higher process temperatures. FIGURE 14 shows the result of a parametric study using different types of stainless steel mesh based resistive elements [7]. In this case, thickness of the wires had been varied as well as aperture size of the mesh, whereby thickness (dotted line) and aperture size increase from the far left to the right.

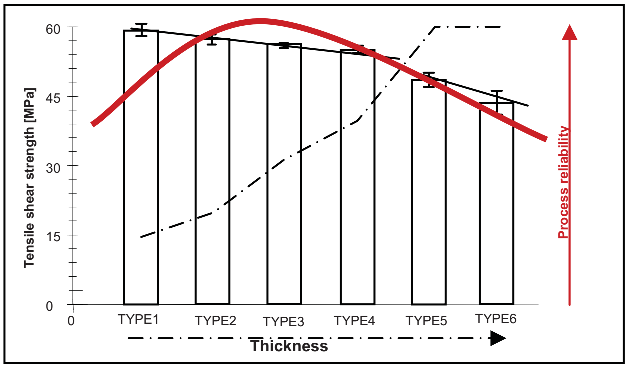

FIGURE 14: Influence of thickness of heater element on shear strength and process reliability

It can be seen, that at decreasing thickness maximum shear strength of the welding is increasing; maximum shear strength is obtained using the TYPE 1 heater element. On the other side, process reliability in respect to strength optimized welding parameters (red line) shows a maximum between TYPE 2 und 3. This means, that for these types nearly 100% of the welding attempts had been successful. In case of reduced process reliability, the resistive element may fuse due to thermal overload at maximum process temperature (for CF-PEEK in the range of 390°C). The fusion has direct impact on the mechanical properties and the standard deviation of the welding (see FIGURE 14). The red curve gives an impression of failed welding specimens depending on the mesh type. As the number of tests may vary for the different elements, no explicit scale was added.

Another Must-have of the heater element concerns with electrical insulation towards the conductive fibres of the structure. To avoid current leakage, decoupling of resistive element and structure has to be guaranteed. If not, if temperature excesses melting temperature of the matrix electrical connection between resistive element and structure may occur. In this case, welding energy is partly guided through the structure itself which causes an incomplete welding and sometimes damage within the carbon fibre part.

Electrical insulation itself here was realised by using non-conductive fibre layers. Within many trials, the use of thin fabrics of glass fibre on both sides of the resistive element has been found to be an easy and sufficient solution. As thickness and, due to this, thermal capacity is increasing; heating-up of these insulated heating elements is much more homogeneous, as can be seen in FIGURE 15 below. In this case, temperature of the element surface was measured by using an infrared camera system of INFRATEC (Germany).

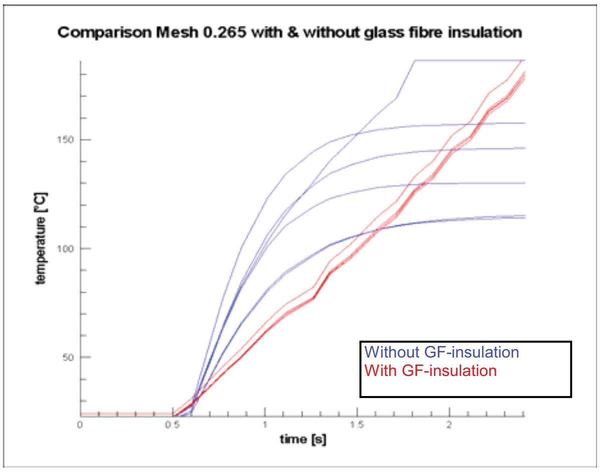

FIGURE 15: Heating-up of stainless steel heater element with and without electrical insulation

Configuration of a heater element embraces the pre-treatment of the resistive element (especially, if metallic elements are used), implementation of the matrix material within the resistive element and application of the electrical insulation. At DLR, Institute of Structures and Design, all actions normally are realised within one single production step, except for the pre-treatment. Therefore, the Vacuum Consolidation Technique (VCT) is used. The clamping area of the element remains untreated and unfilled. Micrographs of some metallic heater elements after welding procedure can be seen in FIGURE 16. Both elements are based upon the same stainless steel mesh. Using carbon fibre based elements for demonstration of the insulation effects is difficult due to identification in case of non-insulated elements, so here the metallic variation had been used.

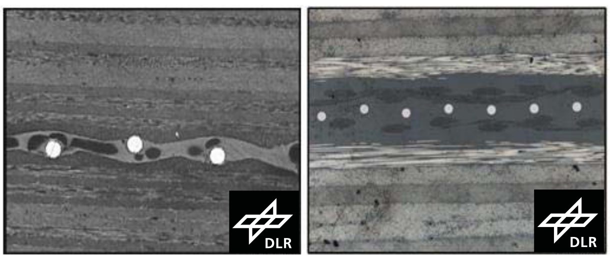

FIGURE 16: Stainless steel heater element without (left side) and with electrical insulation (right side)

As clearly can be seen on the left picture, (conductive) carbon fibres of the structure are in direct contact to the resistive element, though embedding of the element using neat matrix material after configuration was of same thickness as can be seen on the right side. During heating-up, matrix material around the resistive element reaches melting temperature much earlier than structure itself, which leads to a squeezing of the matrix aside the welding area.

When using high-performance thermoplastic materials [8], which means processing temperatures high above 300°C, and regarding the heat conduction by the carbon fibres, this additional matrix layer is not sufficient for electrical insulation. In this case, a short circuit will occur, which leads to local overheating [12] of the interface area and the formation of pores (see FIGURE 16). This is clearly visible when looking on the cavities between the stainless steel wires.

The picture on the right hand side proves that in case of electrical insulation using some thin layers of glass fibre additional matrix material still remains within the resistive element and, due to this, no local overheating is taking place. Therefore, this set-up was defined to be a standard configuration for welding carbon fibre reinforced structure at DLR, Institute of Structures and Design

4. SUMMARY

It has been shown that precise machining of composites by the use of a LASER source without damaging the laminate within the working zone is possible when using a pulsed LASER. It also could be proved that repair of endless fiber reinforced PEEK using a vacuum based consolidation process (VCT) is leading to promising mechanical properties. The current work must be seen as a first step to the development of a LASER-based repair process for endless fiber reinforced thermoplastic composite parts, which is able to be adapted to in-shop and in-field necessities. Until now, the work done at LZH and DLR proved the possibility of accurate processing of carbon fiber reinforced composites without causing heat-affected damage within the laminate.

Furthermore, with a stepped-lap joining and a step rate of 1:20, the repair can recover the static strength about 50 % and the stiffness about 60%. Further investigation regarding additional step rates, the effects of contamination, temperature and moisture and dynamic tests will be carried out.

For integration of the repair patch within the machined structure, the use of resistance implant welding seems to be a promising alternative for thermoplastic matrix materials. Regarding the examinations from the last years at DLR, Institute of Structures and Design, the use of carbon fibres based resistive elements show great potential for substitution conventional stainless steel mesh elements. With the needs of high performance thermoplastic matrix materials concerning high process temperatures, investigation will be based on endless fibre reinforced CF-PEEK. One focal point of this issue will be the adaption of the stepped-lap design for the needs of electrical heat generation within the interface area; especially in combination with carbon fibre based resistive elements.

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