Induction Welding of Hybrid Thermoplastic-thermoset Composite Parts

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Abstract
With the increasing requirements on aircrafts with respect to performance and costs, there is a need for a systematical use of the advantages of different materials and innovative joining technologies. This necessitates inter alia the use of thermoplastic- and thermoset composites. The most promising technology which enables an automated process to join composite parts without rivets is the induction welding. However, the parameters influencing induction welding of thermoplastic with thermoset composites are not yet described in literature. Therefore in this study, the main factors influencing this process the film material, the film thickness and the welding temperature were identified and discussed.

Keywords: Thermoplastic composites, Thermoset composites, Induction welding, Hybrid joining, Aerospace

1 Introduction

In comparison to thermoset composites thermoplastic matrix composites present several advantages such as an increased fracture toughness, a lower moisture absorption, a potential for reduced life cycle cost and recyclability [1]–[3]. These advantages lead to an increasing content of thermoplastic composites (TPC) in aircrafts. However, according to Ageorges, Ye, Hou and Mai [3], [4] the geometric complexity of thermoplastic composite TPCs components is limited, due to the rigidity of continuous reinforcement and the high viscosity of the resin. Therefore, there is no material for every application, so the ideal material for every individual application has to be found [5]. The majority of the helicopter structure consists of thermoset composites (TSC). By replacing TSC components with TPC components, these complementary have to be joined with TSC components. The advantage of the weldability of TPCs should be used to overcompensate the higher material costs of the TPCs. Using fusion bonding technologies can help reaching this goal [6]. With this process the fully consolidated thermoplastic composite parts can be joined without any additives [6], [7]. Two parts are bonded by means of heat and pressure [8]. One of the technologies based on this principle is induction welding, which has already being used for the automated joining of thermoplastic parts in fixed wing aircrafts. Airbus Helicopters is currently investigating this technology to produce and join (TPC-TSC) composite parts. To explore induction welding's full potential for joining hybrid TPC-TSC structures the factors influencing this process were studied. For joining in thermoplastics with commonly used thermoset resins the temperature in the interface during the welding process is one of the main parameters. Another relevant factor is the thickness of the film. Both parameters were examined in this study to analyse if the preferred TPC-TSC material combination can be used. Based on these results further investigations can be performed.

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2 Background and Objectives

2.1 *Joining technologies for thermoplastic with thermoset composites*

For the joining of thermoplastic with thermoset composites different technologies are researched. These technologies are divided into mechanical fasteners, adhesive bonding, co-curing and fusion bonding [9]. Technologies which are commonly used in the industry such as riveting and adhesive bonding have several disadvantages. The main challenges when using these technologies are the additional weight and stress concentrations resulting from hole drilling when using mechanical fasteners [1], [3], [10], [11]. For adhesive bonding technologies the extensive surface treatment is incompatible with the increasing industrial requirements of mass production [1], [3], [10], [11]. The third possibility is to use co-curing as a joining technology [3] which contradicts the approach to reduce the manufacturing costs by using a joining technology. On the other hand the fusion bonding technology of resistance welding is proved to produce joints with high mechanical performances, short process times and a high produceability [3], [9], [12]. The disadvantage of this technology is the high effort for integrating the heating element, so the need of additional research is identified. A fusion bonding technology without heating elements is the induction welding. For this technology no further research has been carried out.

2.2 *Inductive heating and induction welding technologies*

Faraday showed that a changing magnetic field produces a changing electric field and vice versa [13]. The induction welding process is based on this theory. If an alternating current with the frequency *f* passes through a coil, an alternating electromagnetic field around the coil with the same frequency is created. Electrical eddy currents with the same frequency are induced when a magnetically susceptible and electrically conductive material is placed in the vicinity of the coil and its alternating magnetic field. Eddy currents with the frequency *f* are induced in conductive materials which are in the field. For carbon fibre reinforced materials, the field is induced in the conductive fibres. When the current is induced into the fibers, the three principles which are shown in Figure 1 cause the induction heating. For isotropic or orthotropic layups the joule heating is the dominating heating effect [14], [15]. When current flows through the fibers, the generated heat follows the Joule's law [16]. When two fibers are in contact, energy is dissipated due to current flows from one fiber to the next and due to contact resistance. If the fibers are separated by a layer of thermoplastic resin, they act as a capacitor. Consequently, heat is generated by dielectric heating [14], [15]. When the heat energy, generated by the three principles described above, exceeds the thermal losses in the setup, the temperature of the layup rises in the entire material. When the temperature rises above T_g for amorphous and T_m for semi-crystalline polymers, the matrix starts to soften as far as necessary so that a fusion bonding can be performed [14], [15]. After reaching the defined temperature, the layup is cooled below T_g respectively T_m while pressure is applied [14], [15], [17], [18]. Depending on the layup and the geometry the parts will heat up differently in the electromagnetic field. When using an orthotropic tape layup (all fibers point in the same direction), no conductor loops exist and the eddy currents cannot be induced whereas eddy currents can be induced by isotropic layups.

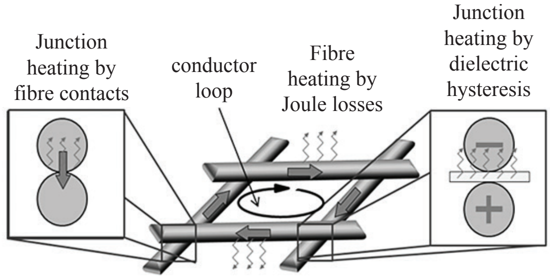


Figure 1: Heating mechanisms.

2.3 *Co-curing of TPC-TSC*

Most thermoplastic polymers are not easily bonded using thermoset adhesives due to their inherently low reactivity, surface energies and polarities [19]. A possibility to resolve this problem is the co-curing process, which leads to interphase between the thermoplastic film and the thermoset part [19]. Fewer studies discussed the phenomena which lead to a strong interphase between thermoplastic films and thermoset resins during the co-curing process. These are described by Vandi *et al*. "through a series of mechanisms, which involve adsorption/wetability at first (strongly dependent on polymer capability), followed by interdiffusion, which can ultimately lead to the formation of a semi-interpenetrating-polymer network or result in phase separation" [20]–[24]. An additional parameter is the Hansen Solubility parameter, which is used to evaluate the compatibility of thermoset resins and thermoplastic films [25]. It defines the cohesion energy of liquids with the dispersion forces, polar forces and bond forces [26], [27]. Besides these material parameters the temperature is the most important process parameter. The temperature determines the viscosity of the resin and also the curing time. Additionally the dissolving of the thermoplastic material is determined by the temperature. For PEI 110°C is the minimum temperature for dissolving by the epoxy resin. The following phase separation takes place at 175°C [20].

2.4 *Thermal degradation of epoxy resins*

Degradation means the decomposition of materials into smaller components. Physical and chemical degradations are possible; in the present case the degradation by thermal load will be considered. The effects of a thermal degradation are depolymerisation, chain scission process or separation of side-fragments to shorter fragments [28]. The oscillation energy of the chain scissions allows only low movements which result in reduction of the strength. A further temperature increase results in degradation [29]. Also the surrounding atmosphere affects the degreadation process. This applies in particular to oxygen. The thermogravimetric analysis, for example, shows a difference between the thermal degradation of epoxy resins in oxygen and nitrogen atmospheres [30]. Free oxygen radicals cause a split of the bonds between carbon- and nitrogen atoms of the epoxy resin structure during a thermal degradation. This creates degradation characteristic carbonyl groups [31].

3 Experimental Details

The aim of this investigation is to predetermine the influence of the film thickness, the polymer and the welding temperature on the mechanical performance of the weld seam. Therefore, heating experiments with different thermoset coupons were carried out first to identify the thermocouple with the lowest heating in the electromagnetic field. In addition, tests to determine the influence of the wire diameter, the influence of the thermal radiation of the induction coil and the influence of an increased temperature on the heating of the thermocouple in the electromagnetic field have been conducted.

3.1 *Materials*

3.1.1 Thermoplastics and thermoplastic composites

Unidirectional tapes SupremTM T 55% AS4/PES-4100 (with 1"; 145 g/m^2 fibre areal weight) made of polyethersulfone (PES) were supplied by Suprem SA (Yverdon-les-Bains, Switzerland). The tapes are made of Hexcel HS-CP-5000-AS4 carbon fiber rovings bundles. The PES matrix is Sumitomo Sumikaexel PES from Sumitomo. Unidirectional tapes TPUD PEI-HTS40 (with 1"; 145 g/m^2 fibre areal weight) with a polyethersulfone (PES) were supplied by Tenax Europe GmbH (Düsseldorf, Germany). The tapes are made by Tenax R HTS40 X011 12k carbon fiber rovings bundles. The PEI matrix is Sabic Ultem 1000 PEI from Sabic (Riyadh, Saudi Arabia). The thermoplastic films Lite S and Lite I with a thickness of 50, 125 and 250 μm were supplied by Lipp-Terler GmbH (Gaflenz, Austria). The PES (Ultrason 2010 PES) granulate is made by BASF SE (Ludwigshafen, Germany) and the PEI (Ultem 1000) granulate is made by Sabic (Riyadh, Saudi Arabia).

3.1.2 Non crimp fabric (NCF) and thermoset resin

The biaxial fabric ECS 6090 with a fiber weight per unit area of 251 g/m^2 and polyester sewing thread is supplied by Saertex (Saertex GmbH Co. KG, Saerbeck, Germany). The RTM resin (HexFlow RTM6) is supplied by Hexcel Corporation (Stamford, USA) [34].

3.2 *Equipment and testing*

The temperatures were measured with the thermologger Yokogawa DX1012. The inductor is a pancake inductor with a diameter of 25 mm and two circuits, manufactured from a 3 mm thick copper wire.

The used induction generator is a CEIA 400 kHz (PW3-32/400) generator.

3.2.1 Non crimp fabric (NCF) and thermoset resin

The manufacturing of the thermoplastic laminates is a two-step process. First, plies were formed on top of a stainless steel tooling plate, coated with a release agent, by tacking tapes with a soldering iron. The stacking sequence for the CF/PES laminates was ((0/90)3s) and for the CF/PEI laminates it was ($(0/90/0/90/0/90/0)_s$). Subsequently, the laminates were vacuum bagged and consolidated in an oven at 400°C (for 60 minutes). The assembly used for consolidating is schematically illustrated in Figure 2. The breather is made of dry glass fabric. The vacuum bag and fixation tape were polyimide based, whereas the sealing tape is a high temperature resistant tacky-tape. The final dimensions of the laminates were 400 mm × 100 mm. The thickness is about 2.5 mm and six specimens were manufactured.

3.2.2 Specimen preparation thermoset laminate

The thermoset plates and those with a thermoplastic film on the surface were manufactured with the vacuum assisted resin transfer molding (VARTM) process. The non-crimp fabric (NCF) layers were cut according to the tooling dimensions 300 × 400 mm. The stacking sequence for the laminates is $(0/90)_{4s}$. The PES and PEI films are cut in the same dimensions, cleaned with ethanol, dried according to the manufacturer information at 140°C (PES) and 160°C (PEI) and fixed in the tooling on top of the NCF-Preform with kapton tape (Kaptontape, Airtech International Inc., Huntington Beach, USA). The infusion temperature is 120°C and the curing temperature is 180°C.

3.2.3 The Fourier transform infrared spectroscopy (FTIR)

With infrared spectroscopy the material is irradiated by infrared light (IR). Energy absorption leads atoms and molecules from ground state to excited state. The energy difference between ground state and excited state is characteristic for the material and corresponds to the absorbed irradiation. This allows the identification and characterization of unknown substances and determination of their purity. For a spectroscopy an

Figure 2: Laminate as prepared for the oven cure cycle.

interferometer is used. It collects the interference due to the variation of the respective wave length. Consequently, the intense of the interference can be shown on the interferogram. The wavelength spectrum is between 3 cm^{-1} and 12500 cm^{-1} [32]. The described carbonyl groups can be detected with this technology and the characteristic wavelength for the carbonyl groups is between 1730 and 1750 cm^{-1}. An increase of the intensity at these wavelengths indicates an increase of the carbonyl groups and thus a degradation of the epoxy resin. A comparison of specimens with different thermal loads shows the degradation degree [33].

3.3 *Specimen manufacturing*

3.3.1 Induction heating procedure of the ILSS specimens

To measure the influence of the welding temperature on the degradation of the thermoset resin during the welding process inter laminar shear specimens are manufactured. To achieve a homogeneous in plane temperature distribution the specimens are heated in a continuous heating process (Figure 3) during which the inductor was moved over the specimen with a speed of 0.1 m/min, a distance of 3.5 mm and at the power shown in Table 1. The listed temperatures are the average of the maximum temperatures measured with the thermocouple type *E* sensors (0.13 mm; OMEGA Germany) on the top of the laminate at the beginning and the end of the welding zone. The pressure during the process is applied by an aluminum roller with a diameter of 40 mm, a width of 60 mm and a distance to the inductor of 5 mm.

Table 1: Welding power and temperature for the ILLS manufacturing

Power [%]	Measured average temperature [°C]	Expected temperature [°C]
10	186	180
12	249	250
16	302	300
22	348	350
28	453	450

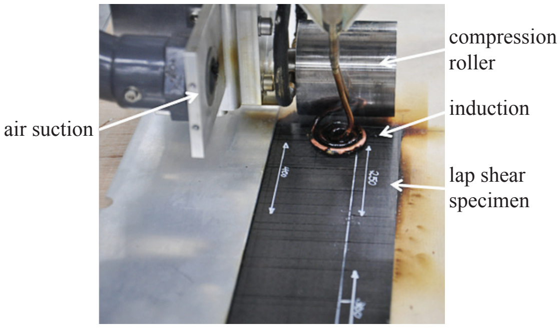


Figure 3: Inductive heating of the ILSS specimens.

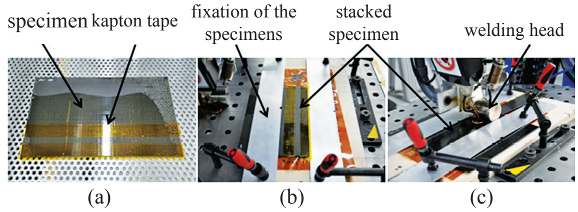


Figure 4: Hybrid joining with the induction welding technology (a) lower plate (thermoset with thermoplastic surface) to prevent edge effects the kapton tape limits the welding seam (b) fixation of the lower plate on the tooling (c) welding process.

3.3.2 FITR-specimens

The CF/epoxy plate is divided in 14 areas and heated between 250°C and 350°C. The temperature is measured in the middle of the pancake coil with the pyrometer. The stationary heating is performed with 2 mm distance between the surface of the specimen and the coil. The heating time up to reaching the final temperature was 7 seconds. After the heating process the specimens are analysed by Airbus Group innovations (Ottobrunn, Germany) with the FT-IR 4100 ExoScan (Agilent Technologies, Santa Clara, USA). An area of 4, 9 mm^2, of every thermal loaded part of the specimen is analyzed.

3.3.3 Hybrid induction welding and lap shear testing

Before welding the surfaces of the thermoplastic and thermoset plates, they were cleaned with ethanol and due to the edge effects the welding seam was limited by kapton tape (shown in Figure 4). In the second step the thermoset laminate was fixed on the tooling with the thermoplastic surface on the top and the thermoplastic plate was positioned with a 52.5 mm overlap and fixed with the tooling. Both plates were joined with a continuous induction welding process with speed of 0.1 m/min, 150 N pressure, 2 mm coil-specimen surface distance and 20% of power. With this setup, an interphase temperature of 300°C is reached (measured with integrated type E thermocouples). After the welding process the inlet and outlet zone are cut. Corresponding to DIN EN 2243-1 6 test specimens with a width of 12.5 mm are sewn. In conflict with the norm there are two kapton tape isolated areas with a width of 20 mm. The influence of these two areas on the results is not considered. For the testing the specimens are clamped with a distance of 50 mm to the clamping jaws (shown in Figure 5). All the tests are performed at room temperature.

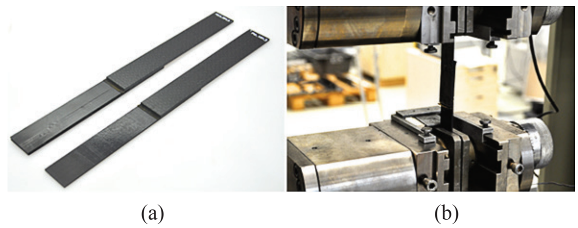


Figure 5: (a) lap shear specimens (b) lap shear test.

3.3.4 Hybrid induction welding and lap shear testing

For the investigation of the joining area with a microscope, specimens with the dimensions 10 × 25 mm are cut. This allows a microscopic analysis of this area and the connection of the thermoplastic film and the thermoset part after and before the welding process. The specimens are embedded in a resin VersoCit-2Kit (Struers GmbH, Willich, Germany), grinded (grain 220-4000) and polished (grain 3 μm).

4 Results and Discussion

4.1 *ILSS specimens*

In the macroscopic examination of the ILSS-specimens (Figure 6), there are no differences found between the reference specimen and the specimen which is heated up to 250°C. The specimen which is heated at 300°C shows a brown color, molten polyester-threads and a delamination between the third and fourth ply. At

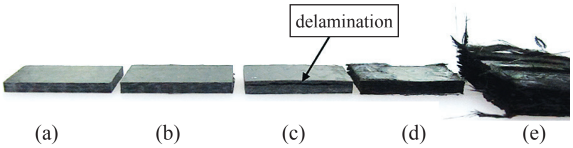


Figure 6: Changes of the ILSS specimens (without thermoplastic film) after the induction heating process at (b) 250°C, (c) 300°C, (d) 350°C and (e) 450°C and as a reference (a) without heating the lower plate on the tooling (c) welding process.

400°C the specimen resin on the top and the lower surfaces are brown and show delamination over the whole thickness of the specimen. At 460°C the resin is degraded completely, a mechanical testing is no longer possible. The requirement of the specification that the thickness has to be homogeneous is only satisfied at the reference, 180°C (not shown in Figure 6) and 250°C specimen (shown in Figure 6). Due to the degradation the thickness of the other specimens increases. In Figure 7 the influence of the thermoplastic films on the surfaces and the influence of the temperature on the ILSS specimens are shown. Between the reference specimens and the specimens inductive heated up to 180°C no decrease of the interlaminar shear strength can be identified. After a thermal load of 250°C a drop of approximately 3% in the interlaminar shear strength in comparison to the reference specimen (without film on the surface) is within the statistical significance, thus it is indicating that a degradation of the thermoset resin does not occur. At a thermal load of 300°C the average interlaminar shear strength drops to approximately 49% and at a thermal load of 350°C it decreases to 9.1% of the reference shear strength without thermal load. A mechanical testing of specimen (d) is not possible due to the high degradation degree of the resin. When reaching a temperature of 300°C on the surface of the thermoset plate a degradation of the thermoset resin must be assumed. It is determined that the use of a thermoplastic film on the surface is not reducing the thermal degradation. As shown in Figure 7 for the specimens without film, with PEI film and with PES film on the surface the ILSS are within the statistical significance for the reference specimens and the specimens with thermal load between 250°C and 350°C. The results are in accordance to the data sheet of the epoxy resin Hexflow RTM6 [34], which shows a glass transition temperature of approximately 180°C.

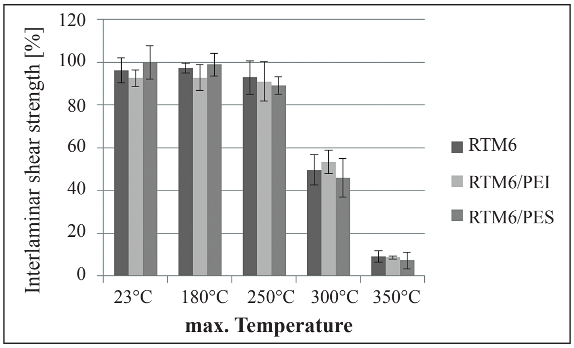


Figure 7: Interlaminar shear strength after thermal load during the induction heating process.

The comparison of the interlaminar shear strength of the specimens with a thermal load of 180°C, 250°C and 300°C indicates that the degradation of the epoxy resin starts also after a thermal load of less than 2 seconds at 250°C. Higher thermal loads than 250°C lead to an accelerated decrease of the mechanical performance due to the further degradation of the thermoset resin. For an identification of the precise start of the thermal degradation further investigation in the temperature range between 180°C and 280°C has to be done. As a result of this research, the temperature of the thermoset laminate should not exceed 250°C.

4.2 *FT-IR specimens*

The results of the FT-IR ExoScan are shown in Figure 8. The data are optimized by a noise reduction and by the shift of the extinction to a common starting point. The high variability of the results can be explained by the surface roughness. However, it is evident that the extinction increases in the area of the wavelength (1730 cm^{-1}) of the carbonyl groups with the temperature. As explained, this phenomenon is characteristic for a degradation of the epoxy resin. The extinction of the reference graph (specimen without thermal load) is the lowest and it increases with increasing temperature (thermal load during the induction heating). The results are consistent with the measurements of the interlaminar shear strength. Between the reference temperature and 250°C the increase of the extinction and therefore the carbonyl groups is low. This correlates with the low decrease of the interlaminar shear strength (3%) in this temperature range. In the temperature range between 250°C and 350°C a significant increase of the extinction

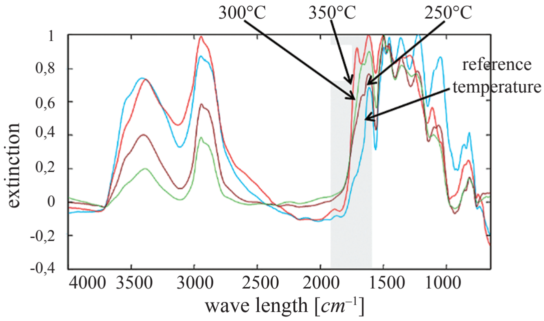


Figure 8: FT-IR ExoScan of the thermal loaded specimens in a temperature range between 20°C and 350°C.

at the wavelength 1730 cm^{-1} was measured as was a decrease of the interlaminar shear strength. Both indicate a degradation of the thermoset resin, which is also shown in Figure 6. Because the gradient of the heating and cooling rate is high, the integral of the thermal load is not influencing the degradation.

4.3 *Microscopic examination and lap shear tests of the induction welded specimens*

In Figure 9 the lap shear strength as a function of film thickness, film materials and interface welding temperature are shown. The reference shear strength (100%) was reached with the CF/PEI-CF/PEI specimens. The highest shear strength (72%) of the hybrid specimens was reached with the PEI-film with a thickness of 250 μm and 300°C interphase welding temperature. With a decreasing film thickness the shear strength decreases up to 36% of the maximum shear strength with a film thickness of 50 μm. The shear strength for CF/EP-CF/PES-specimens is significantly lower. The highest shear strength (38%) for the CF/EP-CF/PES specimens was reached with 250 μm. The lowest value shows the CF/EP-CF/PES-specimens with a 50 μm film thickness. It only reaches 12% of the CF/EP-CF/PEI (250 μm film thickness) welded specimens shear strength. The lap shear strength of the CF/EP-CF/PEI with a 250 μm film is comparable to lap shear values of resistance welded specimens from Ageorges and Ye[3] with a film thickness of 76 μm. Additionally to 76 μm PEI film, a heating element enclosed by two PEI films was used, thus results are not directly comparable. The reason for the different lap shear strength of the PEI and PES laminates gets

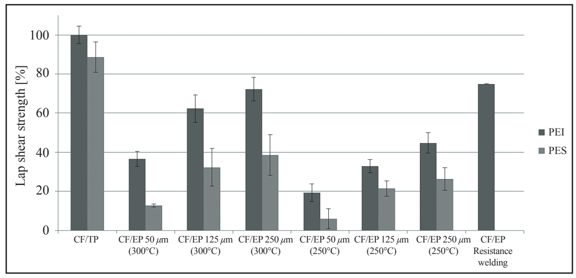
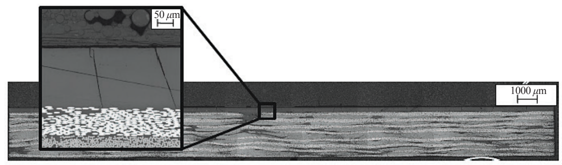
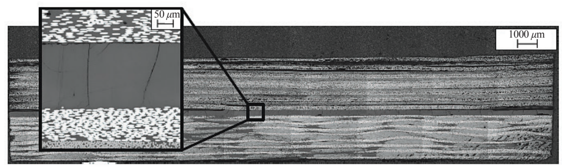


Figure 9: Shear strength of the induction welded thermoplastic PEI / PES-specimens with the thermoplastic (PEI /PES)- and the CF/EP-specimens depending on the thermoplastic film and the film thickness [3].



(a)

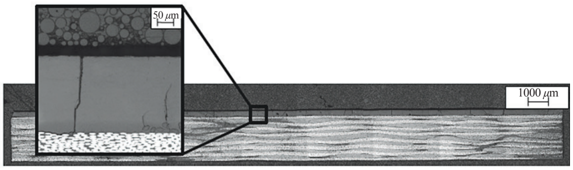


(b)

Figure 10: Microscopic examination of the CF-EP plate with a 250 μm PEI film (a) before and (b) after the induction welding process with the PEI-plate (magnification of 1/25 and 1/100).

evident by microscopic examination of the weld seams. The microscopic images show the interface of the welded specimen before and after the induction welding of the TSC-plate with the thermoplastic film and the TPC-plate. The PEI films did not show a transformation before and after the welding process (Figure 10). It was proven that the vertical cracks are not a result of the welding because the specimens exhibit the cracks before and after the process. Before the welding process a junction of the thermoplastic and the thermoset materials can also be determined for the PES-specimens.

The cracks are not researched in detail in this study, but the origin is to be found probably in the shrinkage stresses caused by the different thermal coefficient of expansions of the thermoset composite and the thermoplastic film. The cracks in the thermoplastic



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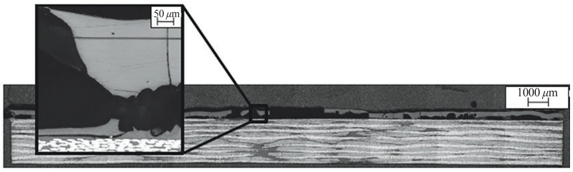
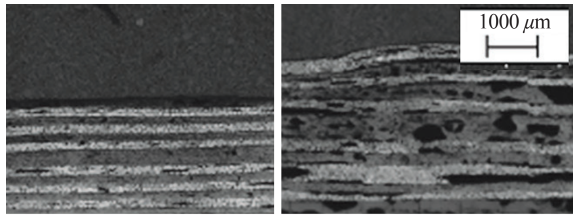


(b)

Figure 11: Microscopic examination of the CF-EP plate with a 250 μm PES film (a) before and (b) after the induction welding process with the PES-plate (magnification of 1/25 and 1/100).

film before the process have no influence to the welding process. The thermoplastic film serves as a material stock for the welding process. When it is welded, it melts completely and the cracks are closed. The difference in the lap shear strength between the PEI and the PES specimens result from peeling off of the PES film from the epoxy laminates during the welding process. Comparing Figure 10 and Figure 11, a significant lower area of connection between the thermoplastic and the thermoset laminate can be identified. One reason for the peel off could be the lower material quality of the PES tapes. The comparison between the welded PES and PEI laminates in Figure 12 shows the difference. The PEI laminates have almost no pores and the same thickness before and after the welding process. The sequential process involves (first heating and afterwards reconsolidation and cooling) the PES laminates expanding in thickness direction after reaching the glass transition temperature due to expanding pores and internal strains that peels off the thermoplastic film from the thermoset laminate. These effects result in a gap between the two laminates and a lower mechanical performance. The increasing lap shear strength with an increasing film thickness is caused by the transition zone between the thermoplastic and thermoset resin. Between the two materials the thermoplastic resin content decreases in direction of the thermoset part [20]. The content of the thermoset resin in the thermoplastic film is influencing the fusion bonding [20] for example during the induction welding process. As shown in Figure 9 the most effective fusion bonding can be reached with a thermoplastic interface with a low thermoset resin content. Due to the short process time a higher welding temperature leads to an increased diffusion between the two parts and a higher mechanical performance which also results from Figure 9 and is in accordance to further research [35].



(a) (b)

Figure 12: Microscopic examination of the CF-TP plate with a 125 μm thermoplastic film after the induction welding process (a) PEI-laminate (b) PES-laminate (magnification of 1/25).

5 Conclusions

The increase of thermoplastic parts in helicopter structures raises the question how to join these parts with the thermoset structures. The induction welding technology was identified as a cost and weight efficient technology in comparison to traditional joining technologies as riveting. In this context the paper focuses on a feasibility-study regarding the most widely spread matrix materials, with RTM6 as the thermoset material and PES as well as PEI as the thermoplastic materials. First the influence of a short-term inductive heating to the mechanical performance of the thermoset laminate was researched. It was shown that when a temperature of 250°C was reached the mechanical performance starts to decrease. The results of the interlaminar shear strength were confirmed by the FT-IR analysis that has shown an increase of the carbonyl groups which indicates a degradation of the thermoset resin up to the same temperature. Based on these results lap shear specimens were welded. The highest lap shear strength was reached with the process parameters 300°C interphase temperature and 0.1 m/min welding speed. With lower welding temperatures reduced lap shear strength was reached. It can be estimated that with epoxy resins with higher degradation temperatures higher lap shear strength can be reached. With an increasing process window the mechanical performance will increase. The research confirmed that a sufficient film thickness has to be used for a high mechanical performance. In the tests films with a thickness of 50 μm and 125 μm lead to reduced lap shear strength. For joining with high mechanical performance a minimum film thickness of 250 μm should be used, also the quality of the thermoplastic tapes has an influence to the mechanical performance. For a higher mechanical performance further research concerning adapted material combinations has to be done. Especially the welding temperature of the thermoplastic laminates should be lower or as close as possible to the degradation temperature of the thermoset laminates.

Acknowledgments

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