21st International Conference on Composite Materials
Xi'an, 20-25th August 2017

SYSTEM IMPROVEMENT FOR LASER-BASED TAPE PLACEMENT TO DIRECTLY MANUFACTURE METAL / THERMOPLASTIC COMPOSITE PARTS

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Keywords: Laser-based tape placement, Selective reinforcement, In-situ multi-material joining, Modular system design; Vertical cavity surface emitting laser (VCSEL) integration

ABSTRACT

The possibility to manufacture economic efficiently structural functionalized parts using high-volume suited processes is crucial to implement lightweight strategies and fulfil the economic and ecologic needs for responsible use of energy and resources. One key strategy to overcome current obstacles of long cycle times and high material costs is to combine metal and thermoplastic composites within one part. Thus, the advantage of having the right material in the right place to fulfil all requirements to the part is used. However, applied solutions to manufacture these kind of multi-material structures still lack in terms of flexibility, productivity, quality and ideal material utilization. One solution for overcoming these current obstacles is the application of the selective diode laser-based tape placement process to locally reinforce metallic parts aiming to generate an optimum weight, reinforcement and cost profile within the part. Key requirement to establish in-situ a sufficient joint between a textured metallic surface and the applied thermoplastic composite tape is the generation of a sufficient heat distribution in both joining partners. Achieving these required conditions becomes even more challenging as both joining partners have completely different thermo-physical and optical properties. Especially, the latter leads to difficulties when using conventional diode laser-based tape placement systems to consolidate tape locally on metal parts, as a local heat input into the metallic component cannot be sufficiently achieved by the diode laser system of these placement units.

The present work deals with initial trials to locally reinforce textured metal surfaces using conventional diode laser-based tape placement. Based on these findings the work derives the concept for a novel laser-based tape placement system which considers the use of Philips VCSEL (Vertical cavity surface emitting laser) technology.

1 INTRODUCTION

The economic and ecologic needs for responsible use of energy and resources are widely acknowledged by science, industry and governments. Thus, the production of hybrid lightweight components combining the advantages of isotropic metallic materials and the excellent mechanical and chemical properties of anisotropic fiber reinforced polymer composites (FRP) comes more and more to the fore. Due to the possibility to manufacture lightweight parts with an ideal weight, strength and cost profile by using these a metal composite material mix, the usage of composites will drastically increase, in particular in the automotive sector. In this manner, the achievement of the objective of an economic production of lightweight vehicles tofulfil the governmental given limits concerning the emissions comes closer.

Although *Dlugosch et al.*, *Lauter et al.* as well as *Dau et al.* justify the applicability concerning crashworthiness and weight saving potential of thermoset-composites combined with high strength steels in structural automotive components [1-3], the use of hybrid metal/thermoplastic composites components in mass applications becomes more and more attractive. On the one hand, the thermoplastic composite materials provide superior energy absorbing capabilities to thermoset composites according to *Jacob et al.* [4]. On the other hand, the absence of cross-links between the polymer chains on a molecular level of the thermoplastic materials enable a melting of the polymer. Hence, parts can be manufactured using an in-situ consolidation process and unlike a thermoset composite, no follow-up curing cycle is needed. As consequence, production cycle times for thermoplastic composites are comparable to the cycle times for conventional thermoplastic processes and can reach the targets for automotive mass production. Further, the use of thermoplastic matrix materials facilitates a material recycling.

A process which enables to process unidirectional continuous fiber reinforced thermoplastic prepregs, so called tapes, and to consolidate these tapes to dissimilar materials using a thermal fusion boding is the selective tape placement as described by *Brecher et al.* [5, 6]. This manufacturing process enables tailoring of the local mechanical performance of components. By local application and bonding of anisotropic tape onto the load bearing areas of a component, the required local increase of stiffness and/or strengths according to the load can be achieved.

Several investigations show that surface preparations on metals like laser texturing or grit blasting enhance the mechanical properties of the bond between and thermoplastic materials [7-10] e.g. in a conductive joining process according to *Engelmann et al.* [7,8] or an autoclave consolidation process as described by *Su et al.* [9]. The investigations of *Jung et al.* [11] as well as of *Furtado et al.* [12] focus on the laser-based joining of thermoplastic composites to metal with no introduced metal surface pre-treatment step.

However, none of these investigations consider the automated tape placement technologies (ATP) like the selective tape placement for joining thermoplastic composites to metal. *Stokes-Griffin et al.* are the first who addressed the challenges of differences in the material´s characteristics concerning laser absorption characteristics, the emissivity to control laser power and bias angle and finally the dissipating heat in the contact zone when locally joining tape to metal with diode laser-based tape placement processes [13].

Based on these finding the present work will focus on the combination of laser-textured steel samples following the findings of *Engelmann et al.* [7] to force a mechanical interlocking between applied tape and textured stell using a diode laser-based tape placement process. The aim is to investigate, if a mechanical interlock between steel and a tape can be achieved and presented obstacles can be overcome. Further, these investigations enable to derive concepts for a novel tape placement system which considers the use of Philips VCSEL (Vertical cavity surface emitting laser) technology to overcome existing issues concerning the reflectivity of the steel as outlined by *Stokes-Griffin et al.* [13].

Therefore, the experimental study focusses on the application of glass fiber reinforce Polyamid 6.6 (GF-PA66) tape to laser-textured AlSi coated USIBOR® steel material specimen in order to focus on the bonding and not on thermal warpage. The effect of different process parameters in particular of the process temperatures on the bond strength will be investigated. The bond strength will be characterised using the mandrel-peel test following *Grouve et al.* [14] and *Su et al.* [9].

2 EXPERIMENTAL

2.1 Process chain to manufacture thermoplastic composite-metal parts

As shown in Fig. 1, the joining process for thermoplastic composites and metal investigated in the present work consists of two processes. The first process is laser-texturing of the metal surface, which will not be discussed. The parameters and the set-up for laser texturing are used according to *Engelmann et al.* [7]. The second process is the conventional diode laser-based tape placement process which enables a melting of the matrix material which is then pressed into the surface texture of the metal. Once the matrix is solidified, a mechanical interlocking bonds both materials together.

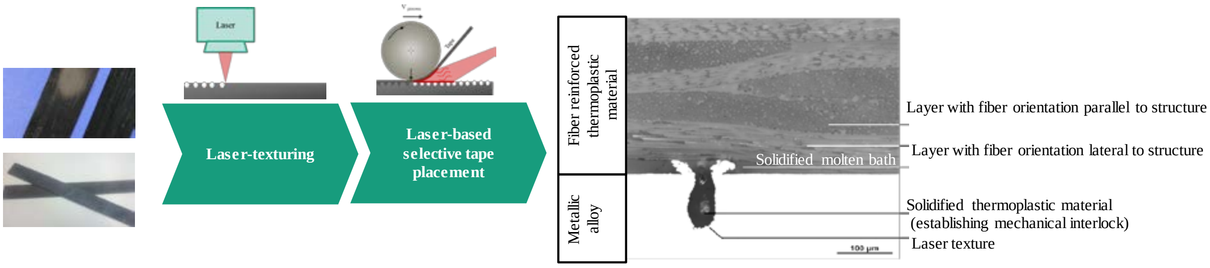


Figure 1: Process chain for investigations of the present work

When combining fiber reinforced thermoplastics and metal alloys using thermal joining operations the establishment of a high bonding strength with minimized remaining residual stresses in the part is still challenging. Often the differences of the thermal and mechanical properties of both joining parts lead to an insufficient bond and the component fails in the material interface or due to thermal warpage the form of the part cannot fulfil the geometrical requirements.

For this reason, two topics need to be addressed in parallel. On the one hand, the materials need to be optimized for joining to establish strong adhesive properties. On the other hand, the thermal heat input into both partners during the joining need to be minimized and only locally applied. To achieve the latter one, the process chain discussed in the present work promises to be the ideal solution. The laser-based tape placement process is characterized by a local and rapidly controlled heat input close to the joining area. This heat input leads to a melting of the matrix material and by applying pressure an in-situ bond is established and no heat treatment or curing is required [15-17]. However, preliminary investigations have shown that the absorbance of a pre-treated metal surfaced is relatively low when using a conventional laser-assisted tape placement system [13]. Hence, the temperature of the metal might not reach a sufficiently elevated temperature for establishing mechanical interlocking. The assumption is that, if the surface temperature of the metal is too cold during the joining process, the matrix will solidify directly when getting in contact with the metal and will not flow into the textured cavities. Thus, a strong mechanical interlocking between metal and tape can not be established. For this reason, the experimental investigations in this paper will introduce a heating of the entire metallic part of the multi-material component to establish a functional joint. The concept for local heating of the metallic part will only be discussed theoretically.

2.2 Tape placement system set-up

The systems utilized for the diode laser-based tape placement process is the Multi-Material-Head tape placement system of Fraunhofer Institute for Production Technology IPT [5, 6, 18] as shown in Fig. 2. This placement system is connected to a Laserline GmbH LDF 3000-40, P_L = 3300W continuous wave diode laser, operating at wavelengths of λ_{diode} = 910 nm, 940 nm and 980 nm. The optical system is composed of an optical fiber and a 1-inch homogenizer optics, which distributes the laser beam into a rectangular shaped intensity distribution with dimensions of w_L = 32 mm and l_L = 67 mm in the focal length.

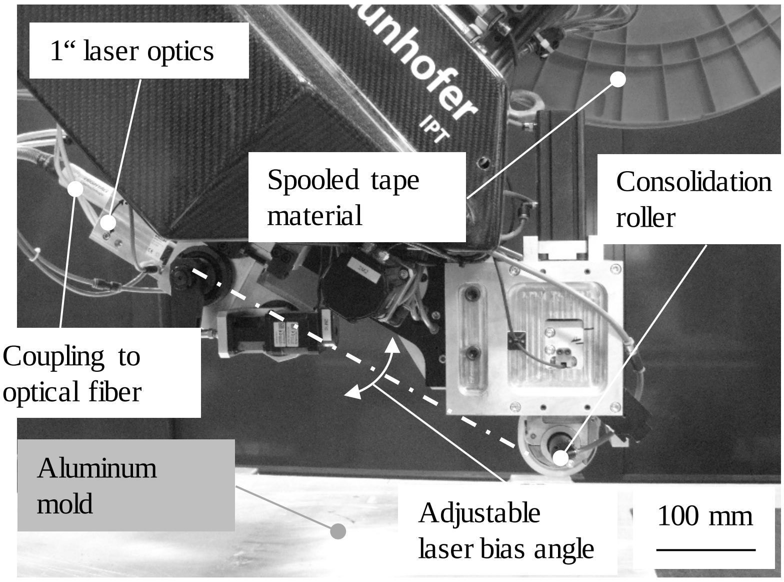


Figure 2: Experimental set up for investigations

The temperature of the incoming tape is captured close to the nip-point using a single point pyrometer from Optris type CTlaser LT F. The temperature of the metal could not be captured with the integrated non-contact measurement due to the operating measurement wavelength of $\lambda_{measure} = 8 - 14$ µm the integrated devices. *Stokes-Griffin et al.* [13] documented same finding. To enable a heating of the textured metal specimen the strips are placed on aluminum mold (see Fig.2, right picture) which can be heated up to $T_{mold,max,desired} = 370°C$, according to the set desired value on the control elements.

3.2 Materials

3.2.1 Laser-textured steel

The steel material used in the investigations is a $t_{steel} = 1mm$ thick hot stamping steel with an AlSi coating from ArcelorMittal sold under the brand name Usibor®. The structure distance resulting from the laser structuring is n = 400 µm combined with a structure depth of about d = 150 µm. The texturing of the metal results in a surfaces roughness of an average $R_a = 6.33$ µm (measured taktile). The arrangement of the structures and the characteristic undercut-cup shape of the structures resulting from the laser sublimation, evaporation and solidification process as described in [7], are shown in Fig. 3.

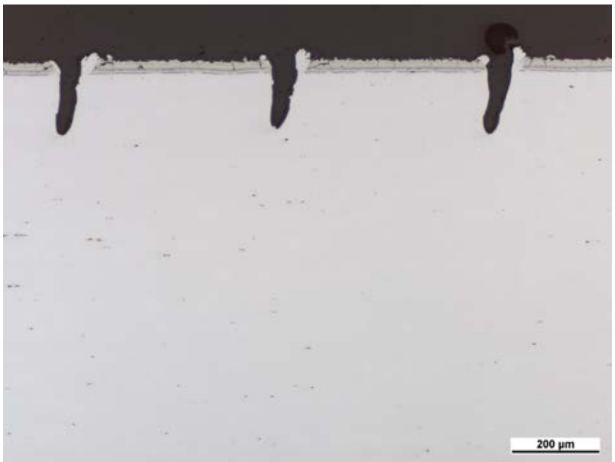


Figure 3: Laser-textured Usibor® with AlSi Coating. Structure distance n = 400 µm, structure depth d = 150µm.

3.2.1 Tape material

For reducing the influence of thermal warpage and distortion resulting from high differences between the thermal expansion coefficients of metal and carbon fibers when joining the dissimilar materials a glass fiber reinforced polyamide 6.6 tape was chosen instead of a carbon fiber reinforced tape. The tape material which properties are highlighted in Table 1, enables the initial investigations to evaluate the feasibility of tape placement onto laser-textured steel in consideration that a sufficient amount of matrix material can flow into the cavities for realizing a mechanical interlocking.

Property	Symbol		GF-PA66
Polymer matrix		-	Polyamide 6.6 including carbon black as heating susceptor
Reinforcing fiber		–	E-Glass
Fiber volume content		[%]	40
Tape thickness	t_T	[mm]	0.30 mm
Tape width	w_T	[mm]	25 mm
Melt Temperature		[°C]	290

Table 1: Properties of tape material used in outlined investigations according to supplier´s information

3.3 Process parameters

For the feasibility tests, the process parameters for the conventional laser-based tape placement process investigated were determined as stated in Table 2. These values are based on past investigations at Fraunhofer IPT as well as derived from the known investigations [5, 6, 16, 19, 20]. The values for the laser power were chosen to ensure that the tape is molten rather then not reaching sufficiently heated condition of the tape. Two full factorial design of experiments were set up, whereas the overall interdependencies between the variation of consolidation force and the change of the mold temperature on the resulting bonding were not fully explored due to a limited number of laser-textured specimen available.

Parameter	Symbol	Unit	Minimum	Central	Maximum
Laser bias angle	α_L	[°]	-	-1.5 (fixed)	-
Consolidation force	F_N	[N]	150	200	250
Laser power	P_L	[W]	2200	2500	2800
Lay-up speed	v_F	[mm/s]	-	150mm/s (fixed)	
Mold temperature	$T_{mold,desired}$	[°C]	180	190	200

Table 2: Tape placement process parameter for feasibility study

3.1 Test specimens and test procedures

The mechanical testing of the bonding properties of the joint was performed on a ZWICK/ROELL Z250 material testing machine. To evaluate the bonding strength the mandrel-peel test set-up following *Grouve et al.* [14] and *Su et al.* [9] was used as shown in Fig. 4. The testing speed is set to v_{test} = 20 mm/min. For each of the investigated parameter combinations two specimen were destructively tested. The fracture toughness expressed by the equation (1) [9,14] was applied. F_a was defined by a dead weight of w_a = 1,3 kg and the friction in the system was determined by testing a non bonded specimen. The bonded width b was determined as average of three measurements of the bonded width of the tape on the metal for each specimen prior to testing. This value differs for each specimen as the tape was not bonded over its entire widths due to misalignment during production.

Further, the tape placement process itself has an influence on the widening of the tape and thereby the bonded width b differs for each parameter combination. To determine the average fracture toughness of each tested specimen the average force measured at the plateau zone (see Fig. 4, right) between the displacements of 10 and 40 mm was evaluated.

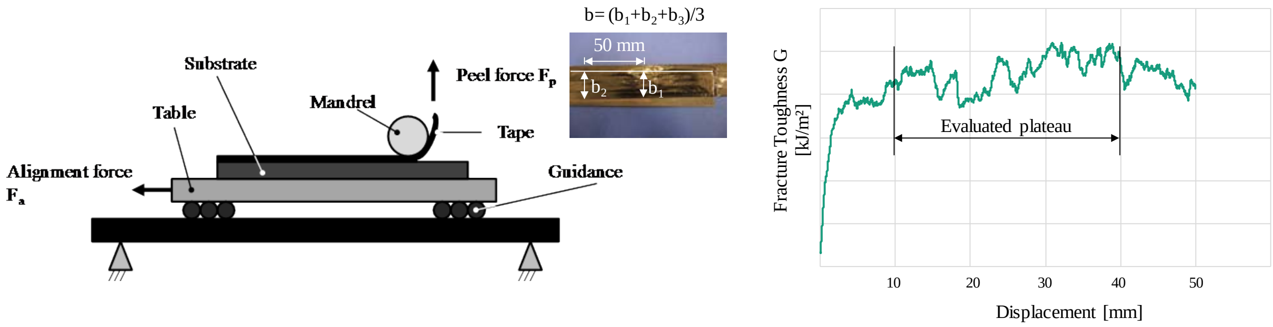


Figure 4: Mandrel peel set-up, schematic drawing (left) and evaluated plateau of the measurement (right)

$$G = 1/b(F_p\text{-}F_a\text{-}\mu F_p) \tag{1}$$

4 RESULTS AND DISCUSSION

4.1 Results of the destructive mandrel peel testing of USIBOR® AlSi-GF-PA66 joints

The analysed test results are shown in Fig. 5. It needs to be remarked that four specimen failed prior to testing. This failure can be attributed to a resulting bonding energy which is not sufficient high enough to prevent the release of the residual strain energy resulting from the thermal joining process prior to testing. The highest measured fracture toughness are G_{max} = 1174 J/m² and G = 766 J/m² resulting from the parameter combination of P_L = 2200 W either with T_{Mold} = 190°C and F_N = 150 N or with T_{Mold} = 180°C and F_N = 250 N. These findings indicate that the highest effect on the bonding strength closely related to the used laser power and thereby on the resulting process temperature of the tape. These findings are pictured in Fig. 5. An increase of the laser power from P_L =2200 W to P_L = 2800 W leads to a decrease of interfacial fracture toughness. An increase of consolidation force assists a better bonding. The effect of the mold temperature in the investigated range is low. However, it needs to be considered that the regarded parameter range has no linear relation between the change of parameters and the resulting fracture toughness as shown by the evaluation of the central point of parameters. Based on the set-up of screening tests, the interactions between the changes of parameters are not analyzed.

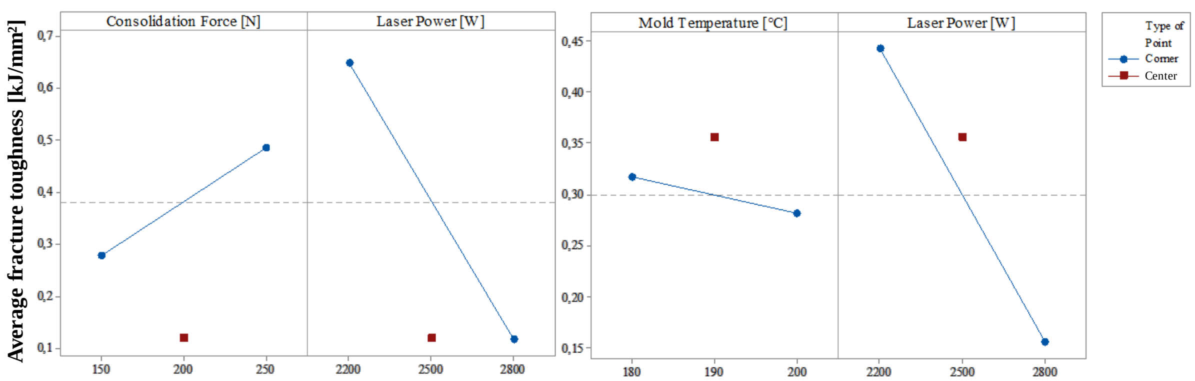


Figure 5: Evaluated test results of two independent Design of Experiments

An optical inspection of the micro section of a bonded specimen shows, that matrix partially flows into the laser-textures (Fig. 6). Nevertheless, not all laser-texture cavities are filled and air pockets can be detected even in the samples which provided the highest fracture toughness (Fig. 6)

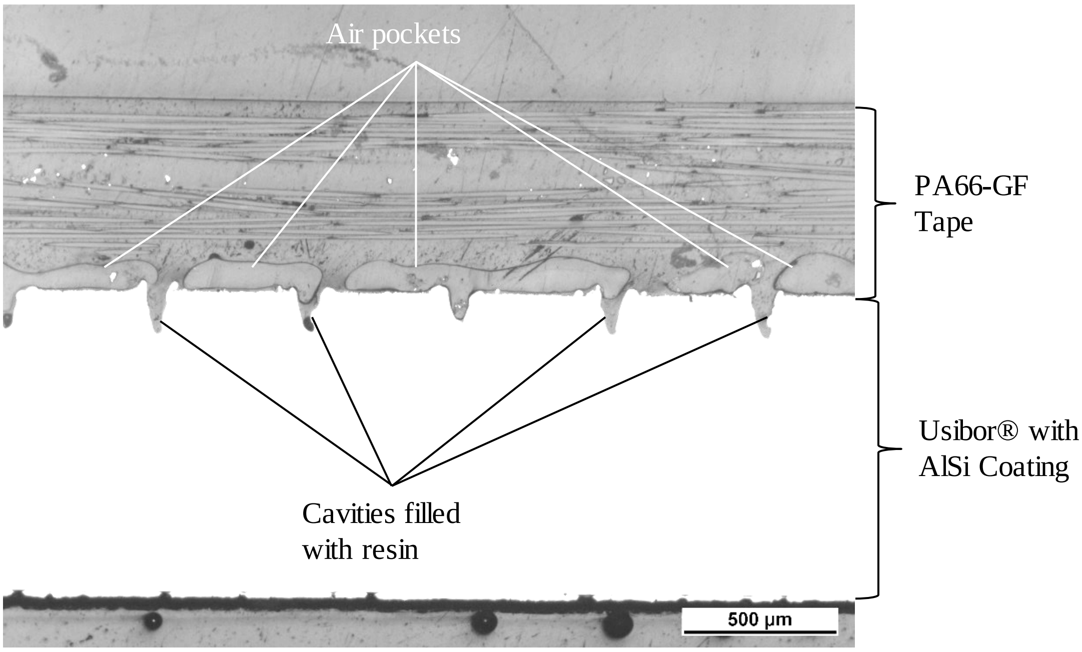
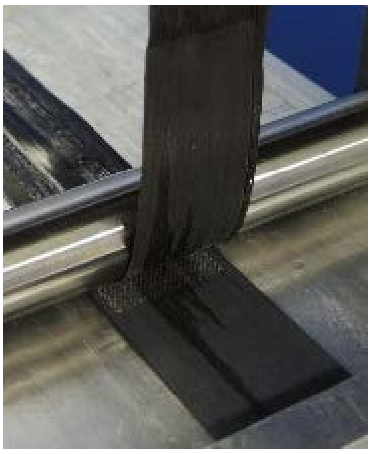


Figure 6: Micro section of the bonded tape to the metal surface

All tested specimens show a single failure mode of an interfacial failure (Fig.7, left) while a little bit of resin sticks to the surface (Fig. 7, right). Micro sections of the metal surface after peeling, as indicated in Fig. 8 on the left side, show that the structures are not peeled out of the laser-texture and remain in the undercuts, where undercuts are. The textures on the outer side of the structure did not provide a sufficient undercut shape. After the mandrel peel test these cavities are only partially filled with resin surface (see Fig. 8, right). The rest of the resin is peeled out of the structures.



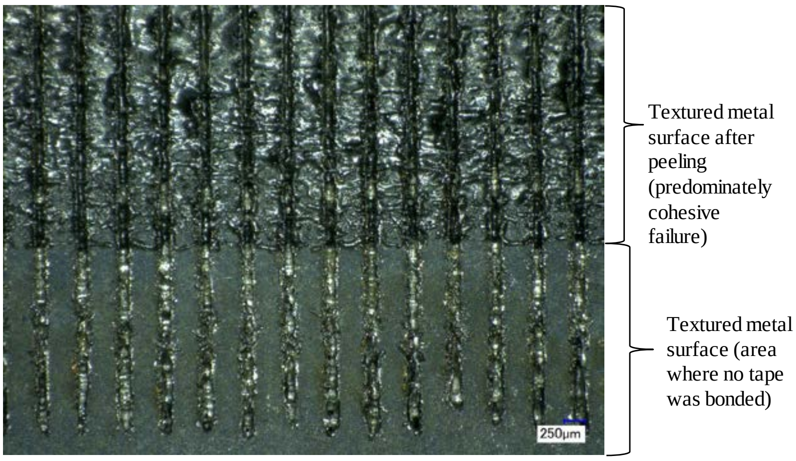


Figure 7: Interfacial failure of the bond during peel testing (left), Top view on metal surface after destructive testing of the bond (right)

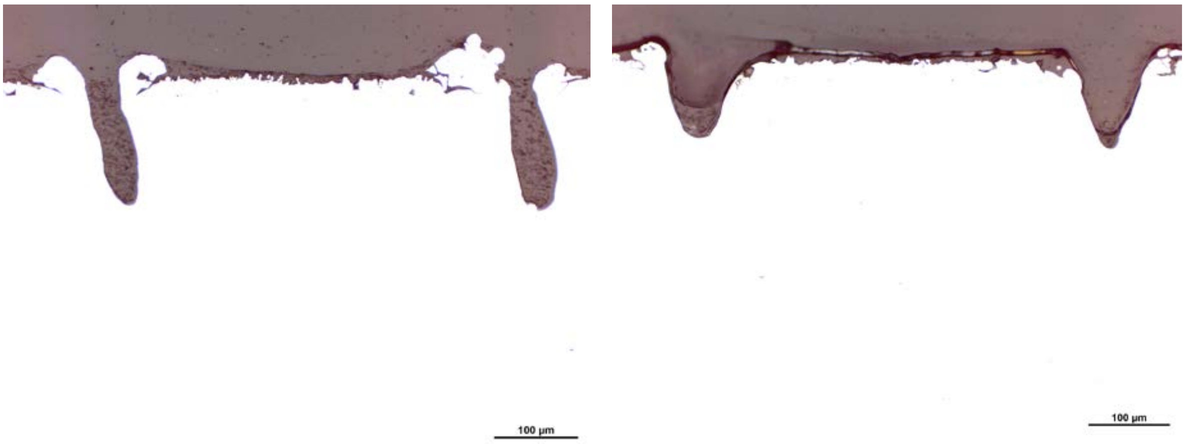


Figure 8: Micro section of a peeled of specimen: Left the middle of the specimen with undercut textures which are filled with resin, Right: Outer part of the specimen with a widely opened texture and no undercut which are only partially filled with remaining resin

4.2 Discussion

Based on the mode of interfacial failure and the indication that the polymer structures do only break cohesively in the micro textured cavities if the textures have a narrow opening and the textures provide an undercut structure. Thus, the mechanical interlocking between tape and metal is only enhanced if the laser structuring process realises this type of structure. If there is no undercut, the peel load lead to an elastic deformation of the polymer, which then slip out of the textures. Thus, an undercut structure is clearly desired, if a load case of a normal peeling force is applied to the bonding. Only then, a cohesive break in the resin occurs and the maximum theoretical bonding strength can be reached. If the positive resin part of the texture is peeled out, the bonding strength is lower. Nevertheless, there is remaining matrix on the surface of the specimen after testing, even in the peeled out cavities. This partially remaining matrix material on the specimen surface may result from physical and chemical bonding but also mechanical bonding due to the natural roughness of the specimen and the micro-cracks in the coating. These structures might result in smaller non-detectable interlocking that lead to a cohesive break inside the resin during peeling.

However, the detected joining forces under peel load are in a comparable range to those which were determined by *Engelmann et al.* [7] and the evaluated fracture toughness of the established bonds do exceed the fracture toughness of the evaluated bonds between titanium and PEEK-CF tapes by *Su et al*. [9]. Nevertheless, it has to be considered that the latter ones did not apply a laser-texturing to the specimens and did only use a grid blasting process to increase the possibility of mechanical interlocking effects between metal and polymer. Further, they measured fracture toughness values for a combination of PEKK-CF with grit blasted titanium that exceed the detected fracture toughness of the PA66-GF with Usibor® AlSi. The increased texture depth of the laser-texturing process combined with the resulting undercut shape allows for drawing the assumption that the bonding forces due to mechanical interlocking should exceed the bonding forces when using a grit blasted metal surface. This should at least be the case, if the cavities are entirely filled with thermoplastic resin during the joining process. These assumptions only consider the mechanical bonding and not the physical and chemical bonding phenomena between both joining partners. As the cavities are not entirely filled in the present investigations the bonding forces are in a comparable range to those evaluated on a grit blasted surface by *Su et al.* [9]. The inspected micro sections (Fig. 6) confirm these conclusions. But the non-entirely filled cavities also indicate that the values for the process parameters are not chosen well to establish the best possible bonding. Records of the non-contact temperature measurements prove this. They show that the processing temperature of the tape is too high for all parameter settings (Fig. 9). As the degradation characteristics for the tape material are not present, the findings of *Rodgers et al.* [21] provide a good estimate on the degradation behaviour of PA66 composites. Shown in the TGA analysis of their findings the increase of degradation of the polymer starts between temperatures of about $T_{degr,PA66} \approx 350$ - 400 °C. This temperature range is exceeded in all experimental trials of the present work. Thus, the degradations has certainly an influence on the resulting fracture toughness. This hypothesis is underpinned by the analysis of the destructive testing which show that the fracture toughness of the bond decreases with an increasing laser power (see Fig.5). Due to a limited amount of resin in the tape it needs to be ensured that most of the available resin material flows into the cavities during processes. A widening of the tape, which is forced by higher process temperatures, as well as an increasing degradation of the polymer leads to a reduction of the available resin and thereby in a decrease of the bonding strength. The degradation also results in the air pockets and thereby in partially non-filled cavities (see Fig. 6, 4th cavity counted from the left side)

Further, the high temperature during bounding may lead to thermally introduced residual stresses. These stresses can result in a cohesive breaking of the resin. In combination with the degradation such cohesive break could also explain the air pockets and voids in the joint (Fig. 6).

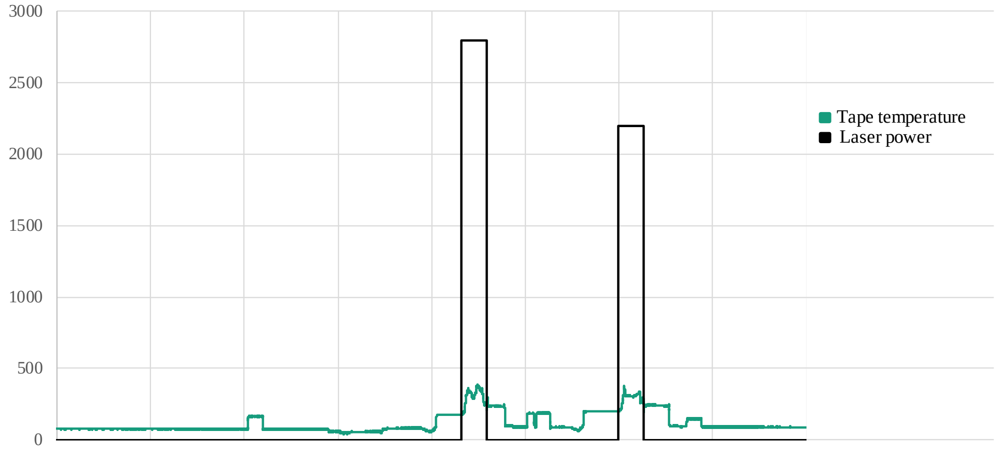


Figure 9: Process data logging of the parameter Laser power (black) and tape temperature (green) during production of two specimen

The chosen ranges for the parameter of the mold temperature do not allow drawing deep conclusions on the effects of this parameter on the achievable fracture toughness. Based on the explanations above the consideration can be made that there are strong interdependencies between the temperature of the tape resulting from the laser irradiation and the mold temperature on the resulting bonding strengths. Both process parameters define the energy respectively the temperature during the tape placement process. This parameter is highly relevant to establish a sufficient joint as explained above. The process temperature needs to be ideal to allow a resin flow into the cavities of the textured metal surface. As the tape temperature is chosen too high in the experimental trials the mold temperature of T_{mold} = 180-200°C does not greatly influence the evaluated bonding. Nevertheless, to reach optimum process conditions both parameters of tape temperature and metal surface temperature need to be optimized in parallel. Considering residual thermal stresses and the entire process chain for hybrid metal and thermoplastic composite parts, the metal surface should only be heated up locally.

An increasing consolidation pressure is beneficial for the process as the resulting pressure from the consolidation roller squeezes the molten resin into the cavities. The interactions between this parameter and the ideal temperature needs to be evaluated in further investigations.

4.3 System improvement

Although the findings above not clearly show what exact local heating of the metal is necessary, a minimum heat input becomes crucial when combining fiber reinforced tape with metal. The findings indicate that an optimum ratio between laser power and substrate respectively metal surface temperature is required to enable a strong bonding. Based on the optical characteristics and the results of *Stokes-Griffin et al.* [13] it is obvious that a conventional laser based tape placement system using the laser bias angle cannot introduce efficiently the local heat input into the metal. The high reflectivity of the metal surface against the incoming laser irradiation of a wavelength of λ_{diode} = 910 nm, 940 nm and 980 nm under an angle of incidence close to $\alpha_{diode} \approx 30°$ does prevent the required controllable heat input. Hence, the conceptual design for a novel tape placement head can be considered. A novel modular tape placement system design and the cross-linked modular control architecture allows for easier integration of additional functions and subsystems. In this way, additional laser systems like VCSEL sources supplied by Philips Photonics can be integrated into the system. The position relatively to the metal substrate surface of this spatial controllable high power laser devices emitting wavelengths of λ_{VCSEL} = 980 nm [22] is crucial to heat up the material locally close to the nip-point. . Hence, the following considerations are taken into account for the conceptual design of integrating the VCSEL into the tape placement system. Although the optical absorption depths of λ_{VCSEL} = 980 nm irradiation on metal is relatively small according to *Brown and Arnold* [23], the absorbance at an incident angle close to $\alpha_{diode} \approx 90°$ is higher than 40% for high strengths steels, spring steels and titanium according to *Emonts* and *Bergweiler* [24, 25]. Hence, the installation space for the VCSEL should be chosen in order to realize an angle of incidence of about $\alpha_{VCSEL} \approx 90°$ between metal surface and laser, considering that back reflections must not damage the laser source. The relatively small optical absorbance depth should prove advantageous for the process, as a minimum heat input into the part is desired in order to reduce thermal residual stresses and warpage and only a surface heating is needed. A further point, which needs to be considered, is the distance between VCSEL and metal surface. Due to superposition of the irradiation of the spatially controllable laser emitters of the VCSEL and the divergence of the irradiation, the distance defines the homogenous irradiated width. Thus, the distance should be determined in order to realize a homogeneous heating over a width which is at least as wide as the applied tape material. Fig. 10 shows a possible integration of a VCSEL into a novel tape placement system on a conceptual level.

Further experimental pre-investigations and simulations need to be carried out to identify the desired metal surface temperature for joining glass and carbon fiber reinforced tape to laser-textured metal and also the ideal position of the VCSEL.

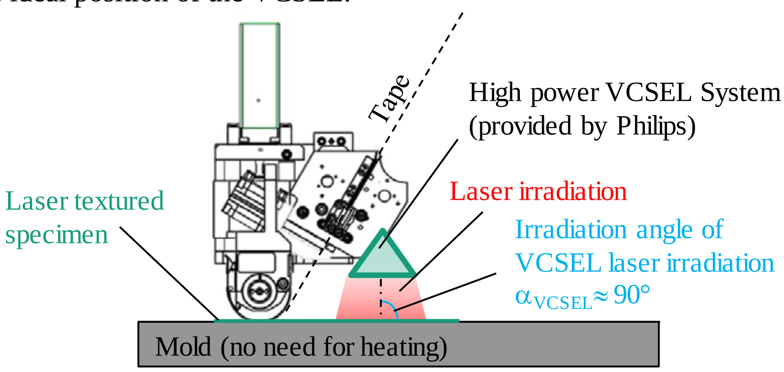


Figure 10: Example for integration of Philips VCSEL into a tape placement system for local heating of metallic part

5 CONCLUSION

Based on an initial feasibility study the effect of various parameters of the laser-assisted selective tape placement process on the bond between continuous glass fiber reinforced PA66 to a laser-textured high strength steel in order to realize a production process for hybrid automotive applications are shown. Additional efforts were spend in order to realize a concept for a novel modular tape placement system which enhances the production process of hybrid parts. By enabling a controlled locally minimized heat input into the metal component, a process with reduced thermal warpage and decreased residual stresses resulting from the different thermal coefficients when joining dissimilar materials should be facilitated.

The determined values characterising the bond between the metal and the applied PA66-GF tape under peel load normal to the surface are comparable to results of other investigations. Nevertheless, it should be outlined that due to the steepness and roughness resulting from the laser-based texturing should exceed the values of the other investigations. These findings underpin the interpretation that the parameter ranges investigated are not chosen well. The set values for the laser power were too high. Thus, the influence of the mold temperature could not be identified sufficiently. The overheating of the polymer during the tape placement process led to an insufficient bonding. Thus, it can be concluded that compared to selective tape placement onto a thermoplastic based substrate the placement process onto laser-textured metal reacts more sensitive on temporary overheating of the tape. The limited amount of resin of the tape is needed to establish the strong bond based on mechanical interlocking. This indicates that the determination of the ideal values for all process parameters, the surface temperature of the metal, the local temperature of the tape and the applied consolidation pressure is crucial. As consequence, further investigations should focus on improving the process parameters under the consideration of reducing the laser power and by investigating all interdependencies between the single parameters. Further trials and different methods of destructive tests need to be applied in order to improve the bonding effects and to identify the limits of selective tape placement onto metal substrates. The investigations have proven that in general it is feasible to combine a laser-based micro texturing process with a laser-based selective tape placement process as the tape provides enough matrix material which can flow into the cavities.

ACKNOWLEDGEMENTS

This work is under the framework of EU Project ComMUnion. This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 680567.

The Authors thankfully acknowledge the financial support as well as the all industrial, academic and research partners contributing assistance to the presented work.

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