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Potential of laser-manufactured polymer-metal hybrid joints

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Abstract

This paper describes a laser-based process to join thermoplastics with metals thermally without the help of any additives. Using PA6.6 and DC01 the main process parameters were investigated with different joining strategies for laser-transparent and nontransparent thermoplastics. For both process variations a failure of the joint within the base material PA6.6 was achieved. It was also shown that there is no correlation between the standardized surface roughness parameter R_a and the shear strength of the joining. The successfully performed joining of PA6 GF45 with DC01 underlines the potential of the described joining method for lightweight design and other industrial applications.

Keywords: laser joining; polymer-metal hybrid joints; lightweight design; surface conditions

1. Introduction

1.1. Motivation

Due to increasing requirements on safety and lower fuel consumption in order to reduce the emission of carbon dioxide, lightweight design is of increasing importance in the field of mobile applications like for example the automotive industry or the logistics sector. Besides these branches lightweight design plays an important role in many other industries when the improvement of efficiency moves in the foreground of new developments. In order to gain the highest possible performance while simultaneously reducing the weight of structural components, the design principle of putting the right material with the right properties at the right place moved in the focus of new structural designs. This results in a mix of different materials such as different types of aluminum alloys as well as high and super high strength steels. The consequent application of these construction principles led to decreasing vehicle weight in the

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younger past. Current trends in lightweight design show the growing importance of plastics and reinforced plastics in order to further reduce the weight of structural components. Considering the specific properties of common as well as new construction materials it has to be expected that the trend of mixing materials will continue in the future leading to new challenges especially for the joining of these dissimilar materials. In order to further implement plastics in structural components and modern production lines new joining technologies have to be developed and systematically qualified.

1.2. State of the Art

Methods to join thermoplastic materials with metals can generally be divided in In-Mold Assembly (IMA) and Post-Mold Assembly (PMA) technologies. In [1] Flock gives a quick overview over various processes and their classification. Several mechanical PMA processes as well as adhesive bonding are already in use especially for small series production in automotive industry. Most common mechanical technologies are classical screwing and snap joints as well as clinching and riveting. In the field of thermal joining technologies friction-based processes, ultra-sonic, induction and laser-based joining are in the focus of current researches [2], [3]. Especially its flexibility regarding work piece geometry, process design and the high productivity make the laser being an attractive tool for the manufacturing of plastic metal hybrid joints. In general there are two variations of the laser based joining process for metals and polymers, depending on the laser-transparency of the plastic joining partner (figure 1).

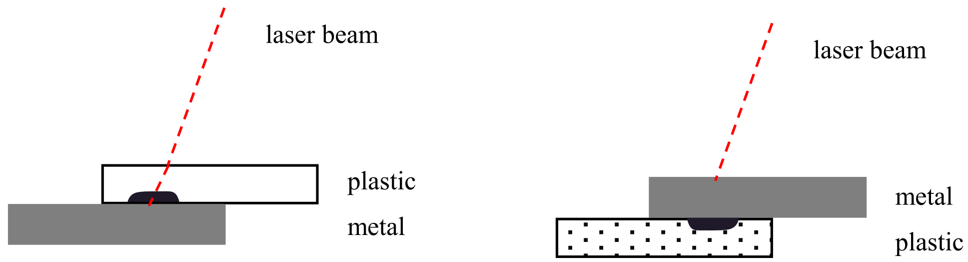

Fig. 1. Schematic illustration of laser-based joining of polymers and metal for (a) laser-transparent thermoplastics and (b) laser-non transparent thermoplastics

For joining laser- transparent plastics with metals, a laser beam is passed through the plastic and heats the metallic joining partner. This leads to an increasing temperature at the boundary layer between plastic and metal. Caused by the temperature increase within the joining zone, the thermoplast melts and moistens the metal surface. Laser transparency is not given for all thermoplastic materials. Particularly lightweight design relevant fiber reinforced thermoplastics with high fiber contents have a low transmission coefficient for the wavelengths of commercial laser sources. In this case the laser interacts directly with the metallic joining partner. The introduced heat is conducted through the metal plate which leads to a temperature increase within the joining zone. All following phenomena are analog to the method described previously.

These process variations are the base for most of the relevant publications regarding laser-based joining of metals and plastics. The so called Laser Assisted Metal and Plastic (LAMP) joining was developed at the Joining and Welding Institute (JWRI) of Osaka University. In [4] the joining of stainless steel with PET, PA and glass fiber-reinforced PA using the LAMP method was shown and high shear strengths were obtained. Further investigations in [5] and [6] were carried out using aluminum alloys as well as different types of plastics. The presented results show that high loads can be applied to the lap joint with separation forces up to 4000 N. The authors did not mention any kind of surface treatment. In order to get an impression of the bonding mechanism the joining zone was analyzed. In consequence of the results the authors assume that there are not only mechanical phenomena causing the strong joint but also physical and chemical bonding mechanisms. In [7] a possible chemical bonding between metal-Cr-O-plastic for the joining of stainless steel is postulated. Besides this there is also the possibility of bonding mechanisms on atomic or molecular levels like Van der Waals interaction forces [8]. In [9] a pulsed Nd:YAG Laser was used in order to produce small holes on the surface of a stainless steel plate. The interpretation of the results shows an increase of the shear strength with increasing structure density. It is concluded that this behaviour indicates a correlation between the tensile shear strength of the plastic-metal joint, the mechanical clamping of the solidified plastic and the created structures on the metal surface.

2. Experimental setup

The experiments presented in this paper contribute to clarify whether a standardized method for surface characterization, like the average surface roughness, is suitable to correlate the surface condition to the shear strength of joining. Besides untreated samples, two different methods for the adjustment of surface conditions were used in order to create regular as well as irregular surface structures. A regular surface structure of the metal joining partner was produced by stamping using a metal plate with protruding peaks which was pressed on the metal plate with a force of 400 kN. Irregular surface structuring was achieved by manual sandblasting using working pressure of 6 bars and corundum with four different grain sizes as listed below was used in order to scale the surface roughness. After the structuring process the specimens were cleaned and the mean roughness index R_a was measured with a perthometer.

- F24 Ø 600-800 µm
- F54 Ø 250-355 µm
- F120 Ø 90-120 µm
- F220 Ø 40-75 µm

As metal joining partner DC01 with a thickness of 1 mm was used. 2 mm thick PA6.6 plates were used as plastic joining partner. In order to clarify the influence of fiber reinforcement a 1 mm thick PA6 sheet with a fiber content of 45 % was tested as well. The overlap of 20 mm was fixed with each plate having a width of 50 mm and length of 75 mm.

The actual joining process was carried out using the experimental setup shown in figure 2. As laser source a fiber-coupled diode laser with the wavelengths 808 nm and 940 nm and a maximum output power of 2.3 kW after fiber-end and a spot diameter of 3 mm was used. The laser was positioned in the middle of the overlap while placing the focus on the metal surface for all trials. Subsequently to the positioning of the metal and plastic sheets within the fixture a constant force of 50 N was applied to joining partners. After a short exposure time the laser moved 30 mm over the surface resulting in a calculated seam of 33 mm length and 3 mm width. The characterization of the joining regarding tensile shear strength was performed using the following test parameters.

- Preload 5 N
- Test speed 10 mm/min
- Clamping length 95 mm

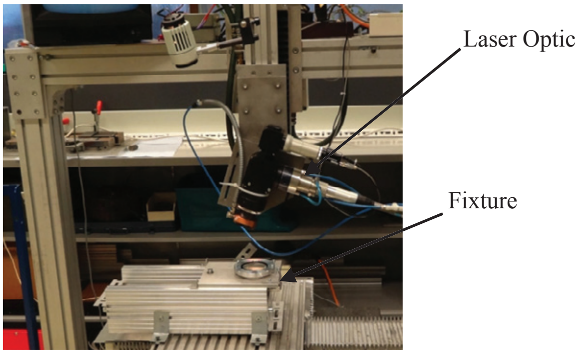

Fig. 2. Illustration of experimental setup for joining tests

During the process optimization a constant failure within the base material of the non-reinforced plastic was achieved. Furthermore peeling stress was observed during the standard tensile shear strength test due to the displaced power flow. In order to provide clear information regarding the mechanical properties of the joined area, the tensile shear strength test was modified as shown schematically in figure 3 by using a new designed test fixture. In the new setup no tensile stress was applied to the PA6.6 and the load was fully applied to joining zone leading to its constant failure. While using this shear strength test it has to be considered that the deformation travel is less than using the standard method due to the lack of deformation of the plastic. In addition the new fixture prevents the lap joint from deformation caused by the displaced stress flow of original tensile shear strength test.

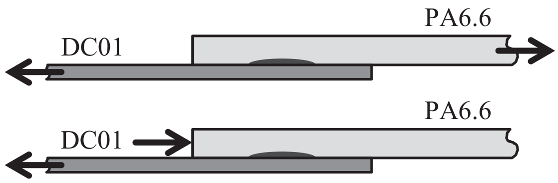

Fig. 3. Schematic illustration of the applied forces standard (upper figure) and modified test (lower figure)

3. Results

Since it can be assumed from the process characteristics that a sufficient temperature is one key factor for the laser-manufacturing of polymer-metal hybrid joints, the influence of the laser power was investigated in the first step. Other relevant process parameters were determined in pre trials and kept constant. The laser power was increased in three steps from 225 W over 265 W up to 305 W with a constant feeding rate of 210 mm/min. Pre trials showed that a short exposure time of 1,4 s at the beginning and 0,4 s at the end of the joining leads to more homogenous seams. The transparency of the used PA6.6 in the wavelength range of the laser source is high enough so the laser beam was passed through the plastic joining partner. The resulting separation forces show a clear maximum for 265 W with approx. 3300 N. At a laser power of 225 W a maximum force of about 2300 N and for 305 W approx. 2700 N were measured. By increasing the laser power the temperature within the joining rises as well and leads to a higher viscosity of the molten plastic and thereby to a better moistening of the metal surface. As a consequence the mechanical clamping after solidification is much stronger. Another reason for the higher shear strength at higher temperatures is the increased heat dissipation. This leads to a broadening of the joining seam which is capable to carry a greater load. In case the laser power and respectively the joining temperature exceeds a certain optimum pyrolysis of the plastic starts. In consequence the formation of pores can be observed as shown in figure 4. Furthermore the photographs show the broadening of the joining seam. The width was measured with 4,6 mm at 225 W, 5,6 mm at 265 W and 8 mm at 305 W.

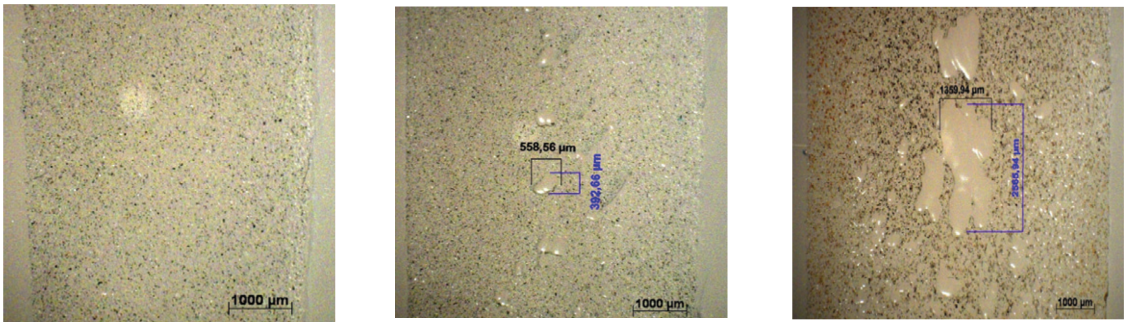

Fig. 4. Formation of the joining seam for laser power of (a) 225 W; (b) 265 W; (c) 305 W

Especially with respect to the potential of the presented joining method for an application in lightweight design structural components the process of joining laser-non transparent plastics has to be investigated. The trials were carried out with a laser power of 265 W while all other process parameters remained the same as in the trials before. As a result of the shear strength test a maximum force of approx. 3100 N was reached which is about 300 N lower than the process with indirect metal heating. Apart from that a much wider spreading of the results was observed. The metallographic investigation shows large pores similar to picture 4 c) as a consequence of pyrolysis caused by exceeding the critical temperature. Besides this the wider joining seam is also a clear indicator for the high temperature within the joining zone which is caused by the higher amount of absorbed energy. When the laser beam is passed through the plastic only about 7 % of laser radiation at 808 nm and 16 % at 940 nm reaches the metal surface. This deficit is not compensated by the better absorption behavior of the sandblasted surface. In consequence more laser energy is absorbed using the process variation with direct metal heating. Concerning these results the feeding rate can be significantly increased for the laser based hybrid joining of metals and plastics using this process variation.

Pre trials showed that the surface conditions have a significant influence on the quality of the joining. One way for surface characterization is the measurement of standardized roughness parameters like for example R_a. In order to clarify whether there is a direct correlation between this indicator and the shear strength of the lap joint, three surface conditions – untreated, stamped and sandblasted – were investigated. Differences of the absorption coefficient caused by the different surface properties of the treated metal were eliminated by heating the metal sheet directly. The laser power was decreased to 250 W leaving the feeding rate constant at 210 mm/min and an exposure time of 2.5 seconds. Figure 5 shows the pyramidal shape which is manufactured by stamping. As shown in figure 6 a) this method reaches the highest surface roughness but at the same time has the biggest variation because of the relatively low structure density compared to sandblasting. The untreated DC01 steel has a roughness of only 1,6 µm but with 1957 N ± 78,5 N can carry more load than the stamped DC01 sheets. According to the findings in [3] and [9] regarding the correlation between the structure density and the shear strength one possible reason for this result is the low structure density of the stamped samples. The cross sectional micrograph in figure 5 shows the pyramidal and smooth shape of the structures produced by stamping. The lack of undercuts and small structures which would support the form and force closure is clearly visible and a first indicator for the importance of the surface morphology for strong polymer-metal hybrid joints.

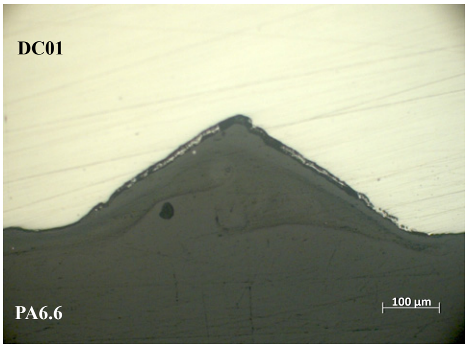

Fig. 5. Microstructure of stamped DCO1 sheet joined with PA6.6

Sandblasting offers the possibility to produce small and irregular structures on the surface of a work piece and further the option to scale the surface roughness by using blasting material with different grain sizes. Figure 6 a) shows the results of the shear strength test for different abrasives. The surface roughness of samples which were sandblasted with F120 and F220 as well as the roughness of the untreated samples is only slightly different. But at the same time the separation force differs strongly. Furthermore there is a significant difference between the surface roughness of the F54 and F120 sandblasted specimens but the difference of the separation forces is within the scattering range. The average surface roughness increases when using the coarsest blasting material but at the same time the separation force decreases compared to F54. According to the cross sections in figure 6 b) there are less fine structures and the structure size increases in case of using coarser blasting material. Considering these results it can be assumed that there is an optimal surface morphology with lots of undercuts and microscopic structures that promote mechanical clamping. Furthermore the results suggest that there is a range for an optimal structure size. It is also possible that a surface treatment decreases the activation energy that is needed to induce other bonding mechanisms like chemical bonding or physical phenomena like Van der Waals interaction forces.

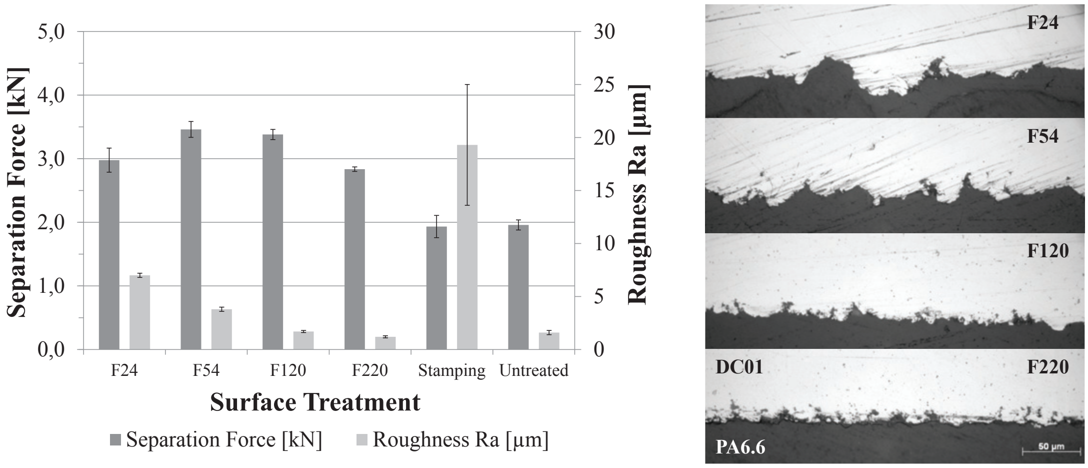

Fig. 6. (a) separation force depending on roughness; (b) cross sections of sandblasted DC01 joined with PA6.6

In order to give an impression for the potential of the presented joining method for future operational fields a glass fiber reinforced PA6 was processed with the same parameters used for laser-nontransparent plastics. The reachable separation force in the tensile shear strength test is with more than 4300 N significantly higher compared to PA6.6. The cross sectional micrograph in figure 7 a) shows that mainly the matrix material is bonded to the DC01 surface but the glass fibers are closely towards the interface. From these investigation it cannot be estimated to what extend the fiber reinforcement has a share in the mechanical bonding mechanisms. However the glass fibers are capable to distribute local stress into the base material. This prevents small local cracks from growing and leads to a higher shear strength. While the PA6.6 sample failed within the plastic base material (figure 7 b) the fiber-reinforced sample showed a boundary layer break on the plastic side comparable to cohesive fracture.

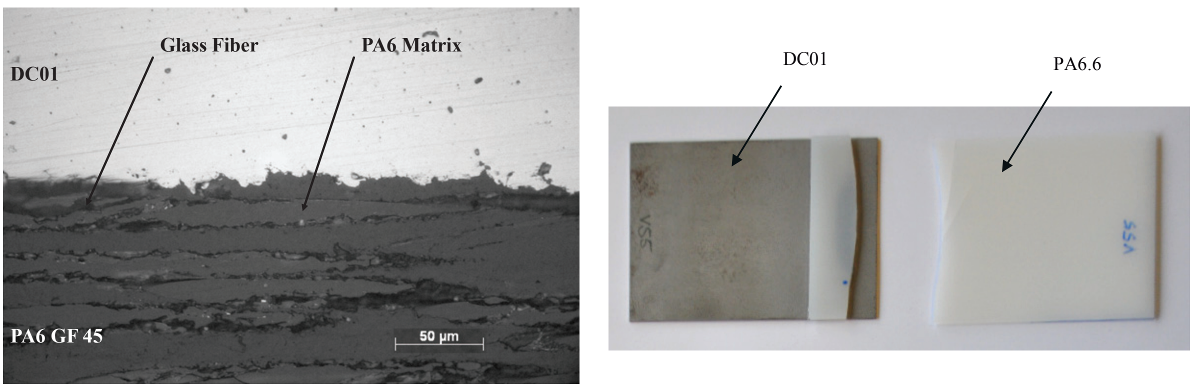

Fig. 7. (a) cross section PA6 GF45 joined with DC01; (b) fracture within the base material of PA6.6 joined with DC01

4. Summary

In this paper the laser-based joining of polymer-metal hybrid joints was investigated. High laser power leads to high temperatures within the joining zone which causes large pores due to pyrolysis of the plastic material. This has a negative influence on the separation force of the joining. By adjusting an appropriate joining temperature the failure occurred in the plastic base material. An investigation on the influence of surface conditions showed that an activated metal surface can reach higher separation forces than untreated DC01 steel with an equal roughness. Further tests indicated that the surface roughness is not suitable as quality criteria in order to predict the strength of a joining. Obviously small and irregular structures with lots of undercuts and a high structure density are beneficial for a strong joint. Consequently the surface morphology is crucial for a high load capacity of the joining. The relatively high separation force of untreated metal sheets suggests the superposition of different bonding mechanisms besides mechanical clamping. However the shear strength can be improved by an appropriate surface structure. In order to provide an outlook regarding the potential of the laser-based joining processes as a future manufacturing technology in lightweight design structures, glass fiber reinforced plastics with PA6 as matrix material were processed. The results show a significantly higher separation force for fiber reinforced PA6 GF45 than for equally processed PA6.6 with DC01 steel. However the role of the fiber reinforcement for the actual bonding mechanism is not yet clarified.

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