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Laser-Generated Macroscopic and Microscopic Surface Structures for the Joining of Aluminum and Thermoplastics using Friction Press Joining

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Abstract

Structural lightweight construction is increasingly utilized in the aerospace and automotive industry. Hybrid structures have great potential, especially with regard to load-specific component layouts. Usually, a surface pre-treatment is applied prior to joining dissimilar materials to improve bonding mechanisms such as form closure. In previous studies pulsed wave (pw) lasers were used for structuring metals. This paper presents the results of aluminum pre-treatment via a continuous wave (cw) single-mode fiber laser: macroscopic and microscopic structures were generated on the aluminum surface; the samples were joined with glass fiber reinforced polyamide using Friction Press Joining (FPJ), a method for joining metals and thermoplastic polymers in lap joint configuration. Using these new methods for surface structuring, shear strength was increased by 40 % compared to previous studies with pw lasers.

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Keywords: Laser Surface Treatment; Microscopic; Macroscopic; Friction Press Joining

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1. Introduction

In the aerospace and the automotive industry structural lightweight construction is essential for reducing the vehicle's overall mass and as a consequence the usage of fuel and energy. Current examples like the Airbus A380 and the BMW i3 show an increasing use of hybrid structures, using different metal alloys and polymers according to the particular requirements of the application. The development of new joining technologies is necessary for these materials since many conventional joining methods are not adequate. As an example, composite structures in the wing of the A380 were attached to the wing's metal skin by bolted aluminum brackets. Cracks occurred in these brackets during the operation of the aircraft leading to damage of the component [1]. A novel method for joining metals to thermoplastic (fiber reinforced) polymers in an overlap configuration is Friction Press Joining (FPJ). FPJ is based on a similar principle as Friction Stir Welding (FSW), except that no pin is used with the tool. A rotating tool is pressed onto a metal workpiece with an axial force (Fig. 1). The friction between the tool and the workpiece generates heat, which is conducted through the metal to the joining area, where the thermoplastic polymer is plasticized. A combination of the axial force and the plasticization causes a wetting of the metal surface with the polymer. The tool is then moved over the workpiece in a continuous movement. After the polymer cools, metal and polymer are joined. The involved bonding mechanisms are believed to be majorly induced by a form closure, but molecular adhesion also plays a role. Therefore, suitable techniques for surface structuring of the metal are required to improve the bonding mechanisms and to form a reliable joint.

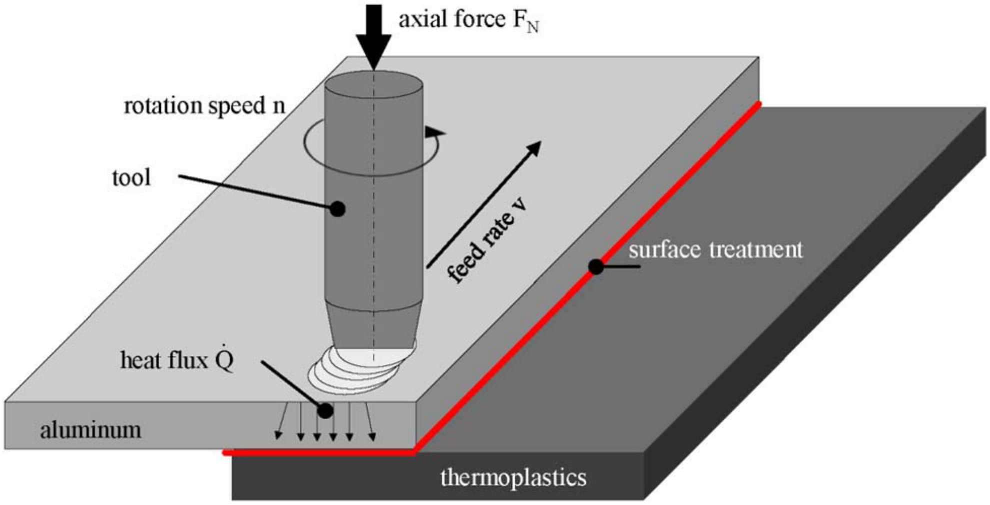


Fig. 1. Principle of Friction Press Joining (FPJ).

2. State of the Art

Fig. 2 shows methods for surface treatment of metals, which can be divided into mechanical, chemical and photonic processes. In previous studies [2, 3] a selection of these methods was examined with regard to their suitability as a pre-treatment of aluminum prior to FPJ with glass fiber reinforced polyamide. The shear strength was tested according to DIN EN 10002-1. Milling did not create undercuts for the polymer and the structures generated caused a notch effect, which led to the failure of the joint. Other mechanical processes like stamping and brushing did not result in high tensile shear strengths. Corundum blasting showed the best results out of the group of mechanical surface treatments with a shear strength of approximately 8 N/mm². Chemical processes like CAA (Chromic Acid Anodizing) created suitable surfaces for FPJ, but the achievable shear strength was lower than for corundum blasting. Additionally, the process of anodizing is complex and requires handling hazardous substances. The highest shear strength of approximately 10 N/mm² was achieved with surfaces structured by pulsed wave (pw) laser systems. The structures generated by this process were nanoscopic to microscopic.

Further studies examined the use of pw lasers for the pre-treatment of metals for subsequent joining processes like laser welding of metals with polymers [4–6]. Defined structures were generated on the surface of the metal by selective material removal. The achievable machining speed was low and dependent on the depth of the structures and therefore on the number of passes of the laser beam over the material. In addition to the material removal, an oxide layer was generated on the surface of the aluminum by the interaction with the laser. RECHNER [7] showed a beneficial influence of this layer for structural bonding.

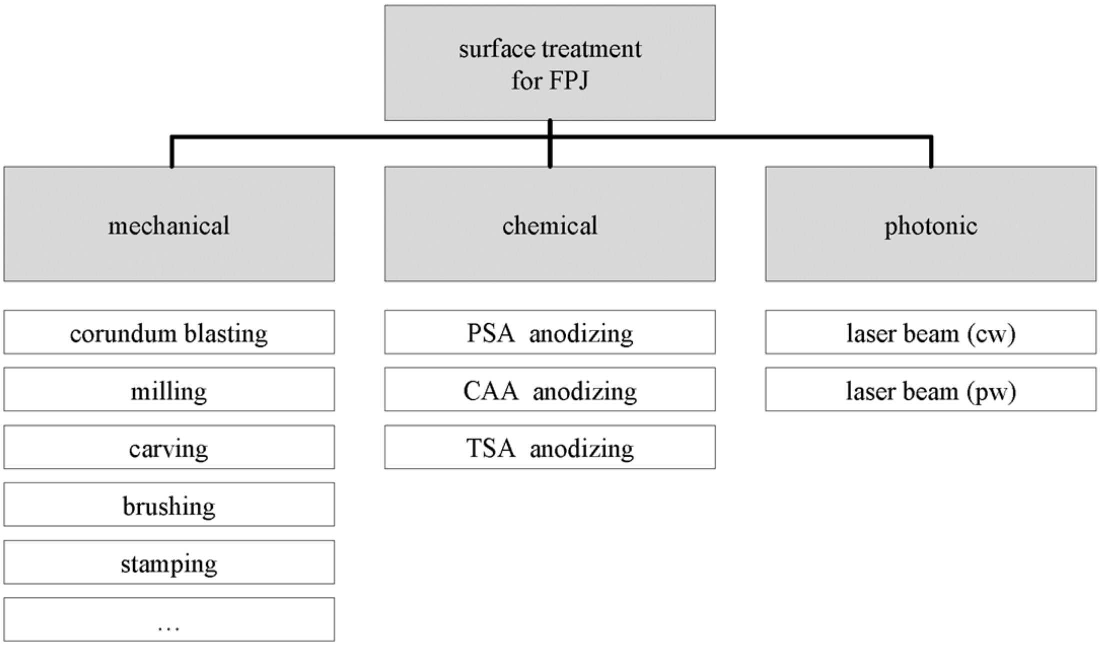


Fig. 2. Options for the surface treatment of aluminum for FPJ.

While surface treatment with pw lasers is common, the use of continuous wave (cw) lasers for this purpose is rarely found in the literature. EARL et al. [8, 9] presented a method using cw lasers for the generation of pins with macroscopic dimensions on the surface of metals, known as Surfi-Sculpt. During the process, the laser beam is guided over the workpiece, generating a melt pool (Fig. 3). If the scanning speed exceeds a certain value, the melt is accelerated in the opposite direction of the spot motion, based on the humping phenomenon [10, 11]. The melt solidifies and, if several passes are applied, the material is successively shifted, generating a pin. The scanning paths can be arranged in a star configuration, and the hereby created pins are sturdier than pins created by passes in a single direction.

Another method for surface treatment of metals with cw lasers is the use of Remote Ablation Cutting (RAC). In RAC, a high intensity laser beam is guided with high velocity over a workpiece. The material in the interaction zone is partially evaporated and the pressure of the vapor ejects the surrounding melt. A kerf is formed, and with subsequent passes the kerf deepens. The ejected material partially solidifies when leaving the kerf and a small burr occurs on the surface [12, 13].

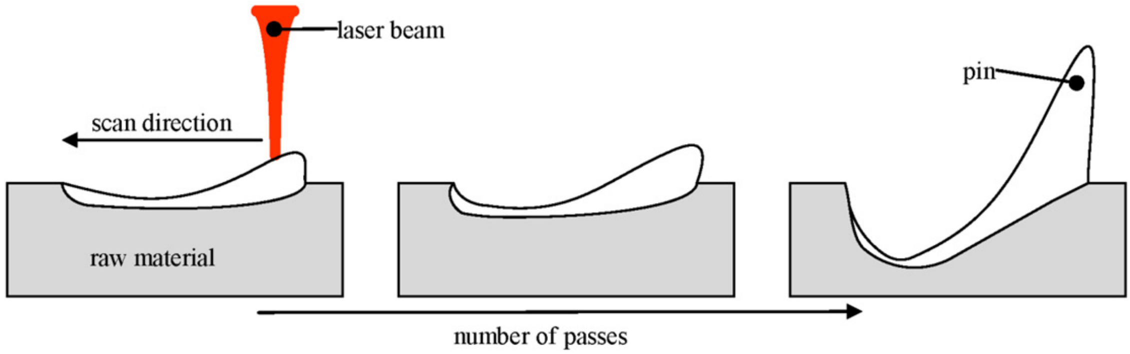


Fig. 3. Principle of laser-based pin generation using the humping phenomenon, based on [8, 9].

3. Objectives

To date, laser surface treatment of metals prior to thermal joining with polymers was mainly conducted using pw lasers. With FPJ, mechanical and chemical processes are used for surface treatment in addition to pw lasers. Since the dominant bonding mechanism for FPJ is form closure, aside from nanoscopic structure sizes, microscopic to macroscopic structure sizes seem suitable for a durable connection between polymers and metals as well. In this study, an analysis of the potential of two different methods for surface treatment using cw lasers will be presented. Macroscopic pins will be generated using Surfi-Sculpt and a modified RAC process will be developed to structure metals on a microscopic level. The suitability of the above mentioned surface treatments for FPJ will be evaluated by a comparison of the achieved shear strength.

4. Experimental Setup

2 mm thick pieces of aluminum sheet metal (EN AW-6082) were structured using a 3 kW single-mode fiber laser at a wavelength of $\lambda = 1070$ nm and scanning optics. The beam profile was measured at a laser power of P = 1,000 W. The focus diameter was $d_{86\%} = 48$ µm, the rayleigh length $z_R = 1.1$ mm, and the resulting beam parameter product BPP = 0.5 mm*mrad. The sheets were clamped on a copper plate to prevent warping. A cross jet was used to prevent spatter pollution on the optic's protective glass (Fig. 4). The aluminum sheets were structured in two different ways. Macroscopic pin structures were generated using Surfi-Sculpt, and the corresponding laser parameters were determined to create reproducible pin heights. Microscopic structures were generated using a modified RAC process. Several passes of the laser beam were applied to obtain shallow kerfs in the material. Beforehand, studies were conducted to determine the influence of the scanning speed and the laser power on the ablation of EN AW-6082.

The pre-treated aluminum sheets were then joined to glass fiber reinforced polyamide (PA6 GF15, PA6 GF30) using FPJ. The sheet thickness of the PA6 GF30 was 5 mm for the samples with macroscopic pin structures and 3 mm (PA6 GF15) for the samples with microscopic pin structures, respectively. The experiments for joining were carried out on a 4-axis CNC milling machine. A tool with a diameter of 15 mm was used. The rotational speed was set to n = 800 rpm and the feed rate was $v_f = 240$ mm/min. A tilt angle of 0.5° between tool and workpiece was used. The axial force F_N was controlled by the milling machine in a range from 1.5 kN to 2.0 kN.

Samples were tested with regard to their tensile shear strength according to DIN EN 10002-1. Therefore, two samples were cut per sheet using abrasive water jet cutting (see Fig. 5 for the dimensions of the joined sheets and the resulting samples for tensile shear testing).

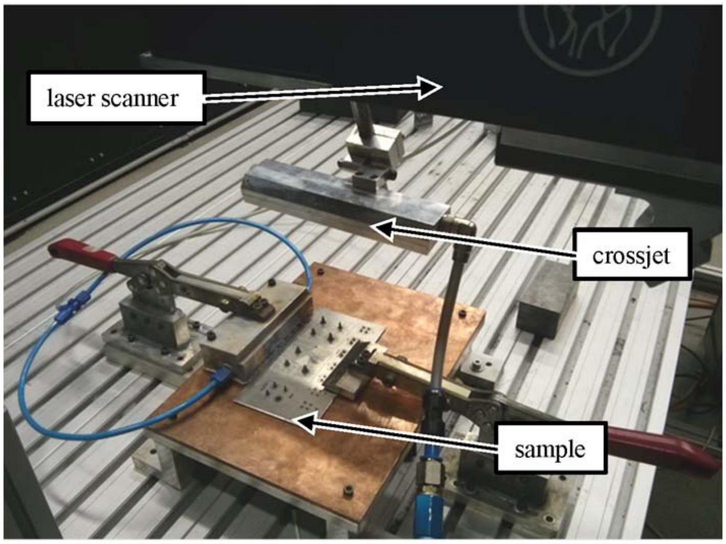


Fig. 4. Experimental setup for laser structuring.

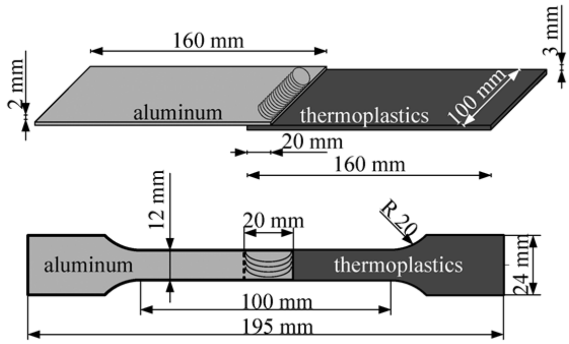


Fig. 5. Schematic diagram of the lap joint configuration and shear tensile test samples.

5. Results and Discussion

5.1. Macroscopic Structures

Pins were generated using Surfi-Sculpt. The scanning paths were arranged in a star configuration, which generated a pin in the middle of the star. The laser beam was guided over the arms of the star from the center outward. The number of arms highly affects the strength of the pin, with more arms resulting in higher strength. The structure height increased with the amount of passes n, whereas a saturation of structure growth could be observed at a certain number of passes. The number of passes was chosen between n = 5 and n = 10 to get pin heights between 1.2 mm and 2.8 mm. A compromise between strength, processing time and heat input was obtained at 16 arms. The entire overlap area was structured; the distance between the pins was 3 mm (compare to Fig. 6 c and Fig. 7 a).

The samples were joined with 5 mm thick sheets of PA6 GF30. FPJ heated the aluminum sufficiently to plasticize the polyamide and embed the pin structures completely (Fig. 6 b). The cross sections of the material also showed an even distribution of the glass fibers in the polymer. All samples failed in the polymer during tensile shear testing (Fig. 6 a and c). A failure of the pin was not observed. The length of the overlap area could not be decreased to generate such a failure, since FPJ requires a minimal overlap length depending on the used tool geometry. The pins caused a high notch effect in the polymer, therefore the polymer failed at the first row of pins.

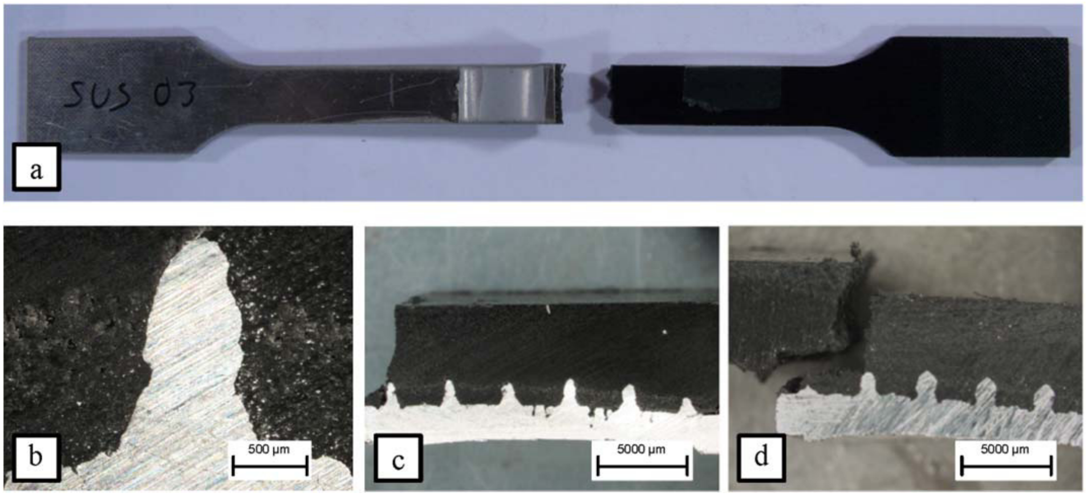


Fig. 6. FPJ of samples structured in macroscopic dimensions: (a) shear tensile test sample, (b) cross section, (c) specimen with equal pin heights, and (d) specimen with tapered pin heights.

The shear strength is highly dependent on the pin height (Fig. 7 a). Higher pins increase the notch effect, therefore the highest shear strength of approximately 10.4 N/mm² was found with the shortest pin heights of 1.9 mm. An increase in pin height decreases the achieved shear strength. Hence, the process of generating pins was modified. Fewer passes were used on the first rows of pins, and the number of passes was gradually increased towards the end of the overlap area (Fig. 6 d and Fig. 7 b). As a result, the pin heights for these samples were tapered. The goal of this trial was to reduce the notch effect at the first row of pins in the overlap area by decreasing their height. The results of the tensile shear test for samples with this surface preparation are shown in Fig. 7 b. The shear strength clearly improved, with values up to 14 N/mm², a 40 % increase compared to previous studies with pw laser systems. The height of the first row of pins has an significant influence on the shear strength of the joint: shorter pins in the first rows result in higher shear strengths.

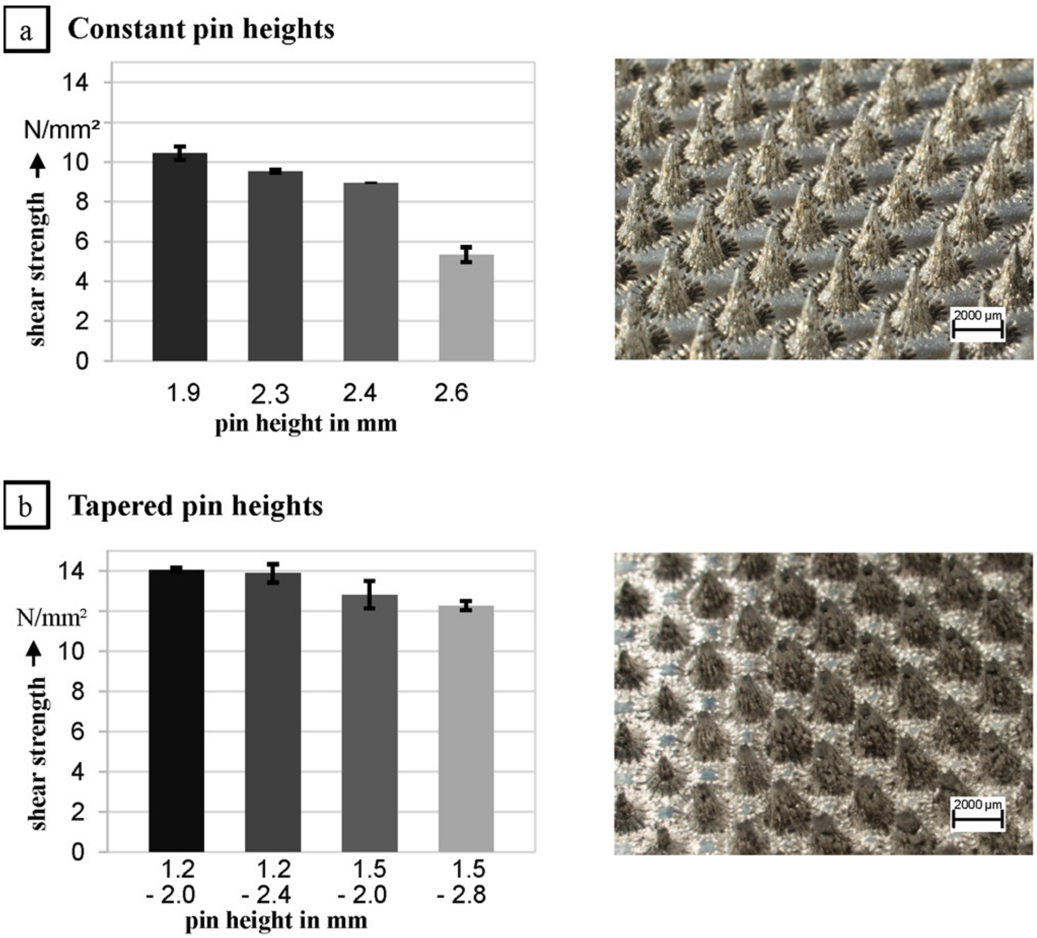


Fig. 7. Shear strength of a lap joint with macroscopic surface treatment depending on the pin height; (a) constant pin heights; (b) tapered pin heights.

5.2. Microscopic Structures

Microscopic surface structures were generated with a modified RAC process. The process window of RAC was determined for the aluminum alloy EN AW-6082 (Fig. 8). At laser powers between 600 W and 3,000 W, deep penetration welding occured at low scanning speeds. In Fig. 8, deep penetration welding can be observed at scanning speeds up to 1,000 mm/s. With increasing scanning speeds, the melt is partially ejected and a kerf is formed. The transition between deep penetration welding and RAC depends on the laser power; at higher laser powers, higher scanning speeds are required for the melt ejection. The depth of the kerf, e.g. at a scanning speed of 10,000 mm/s, depends on the laser power: with higher laser powers a deeper kerf is formed. This can be explained by a higher line energy (energy per length unit) and therefore a larger volume of molten material. At a laser power of 3,000 W the maximum scanning speed of 10,000 mm/s is not sufficient to completely eject the melt from the kerf.

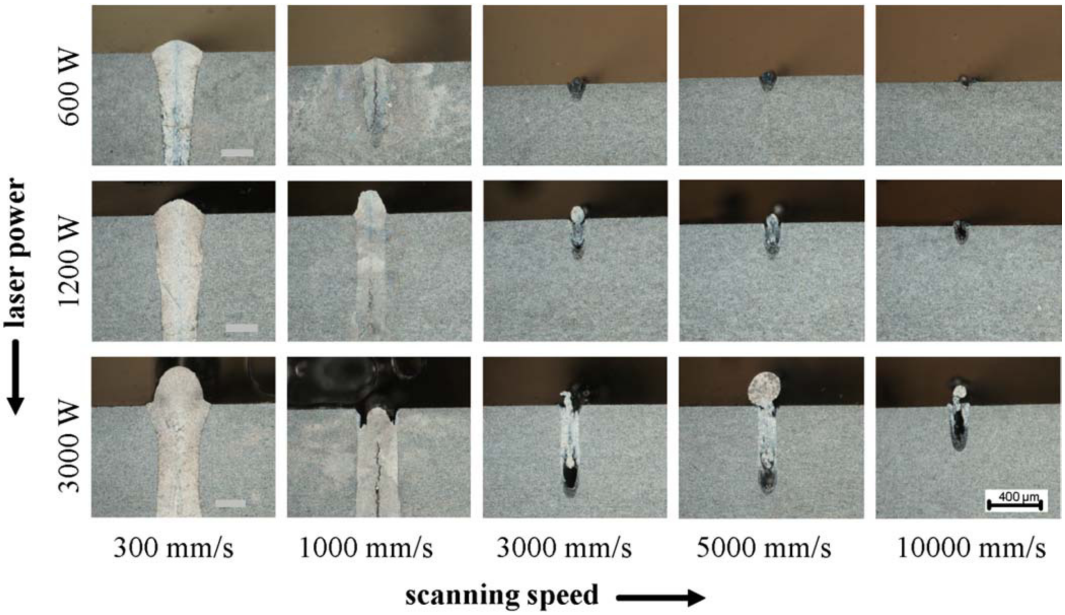


Fig. 8. Cross sections, showing the transition from deep penetration welding to Remote Ablation Cutting.

The aluminum samples were structured with the determined laser parameters for RAC. A distance of 0.2 mm was chosen between two scan paths, and consecutive rows of kerfs were formed on the surface. In a next step, the scanning was repeated with the same parameters at an angle of 60° and 120° to the original direction, forming a uniform microscopic structure on the surface. Microscope and scanning electron microscope pictures of the surface revealed large undercuts, caused by the kerfs and burrs. The surface was significantly increased. The ratio between the area of the structured and unstructured surface, defined as the filling factor, was measured using a confocal laser scanning microscope. The roughness values R_a and R_z were measured using tactile measurement.

The samples were joined to 3 mm thick PA GF15. The polymer filled the kerfs and created a form closure with the aluminum surface. Air pockets were found in the polymer close to the interface to the aluminum (Fig. 9).

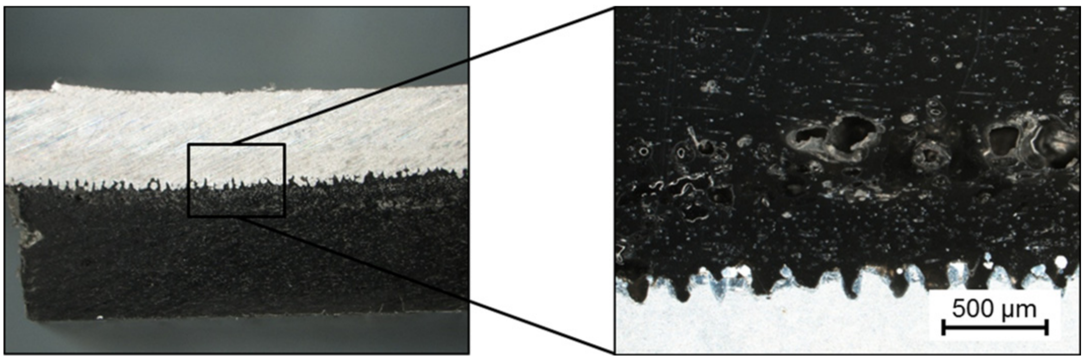
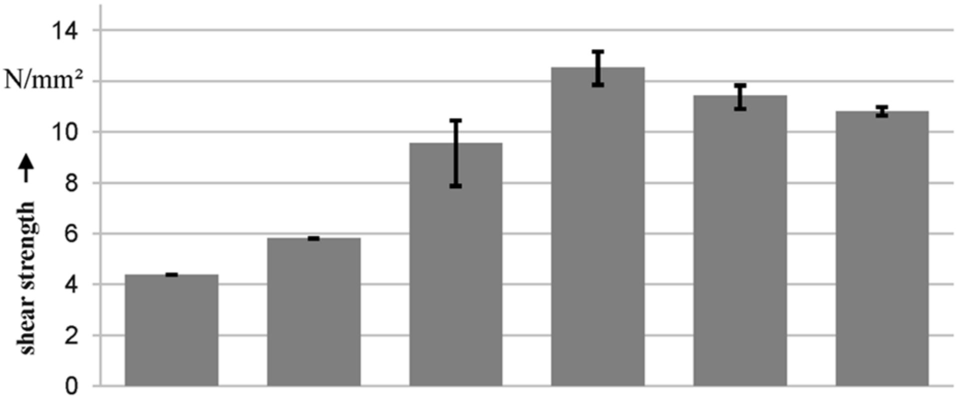


Fig. 9. Cross section through a lap joint with microscopic surface treatment (P = 900 W, v = 10,000 mm/s).

The influence of the laser parameters on the surface structure was investigated with a tensile shear experiment. The shear strength was found to be dependent on the laser power: low laser powers generated small kerfs and undercuts and therefore comparatively low shear strengths could be achieved. Adhesive failure at the interface between polymer and aluminum was observed. The shear strength increased with the laser power. At laser powers above 450 W cohesive failure mechanisms occurred. The highest shear strength of approximately 12.5 N/mm² was found at a laser power of 900 W and a scanning speed of 10,000 mm/s. This is a 25 % improvement compared to previous studies with pw lasers. At this set of parameters, the polymer failed by breaking in the base material. The roughness and the filling factor increase with the laser power. Therefore, the polymer has a larger surface area with which to bind and more undercuts enable improved binding based on form closure. A further increase in laser power over ≈ 900 W resulted in a decrease in shear strength. The roughness and the filling factor continued to increase, but the surface of the structures became more rounded due to the high energy input. Therefore, the form fit on a microscopic level was reduced, and the overall binding of the polymer was degraded.



laser power (W):	450	450	600	900	1200	3000
scan speed (mm/s):	3000	5000	10000	10000	10000	10000
roughness R_a/R_z (µm):	1.5/25	9.6/51	13.3/85	14.1/96	75/241	80/250
filling factor (-):	-	2.4	3.4	7.2	12	-

Fig. 10. Shear strength of a lap joint with macroscopic surface treatment depending on the laser parameters and the surface topology.

6. Conclusion

Aluminum surfaces were structured on a microscopic and a macroscopic level prior to joining with a thermoplastic polymer using the novel process Friction Press Joining. A continuous wave single-mode fiber laser was used for the pre-treatment of the aluminum. The shear strength of the joints was analyzed depending on the surface structure using tensile shear tests.

Macroscopic pin structures were generated using the process Surfi-Sculpt. The shear strength of the joint was found to be dependent on the pin height; the shear strength decreased with an increase of the pin height. Higher pins caused a larger notch effect and weakened the joint. Therefore the pins were manufactured in a tapered fashion, which resulted in an increase of the shear strength. The highest shear strength was approximately 14 N/mm², which is a 40 % improvement compared to previous studies with surfaces structured by a pw laser.

The aluminum surface was also structured on a microscopic level using a modified RAC process. The laser power and scanning speed were highly influential on the structures' topologies. With higher laser powers, deeper kerfs and larger undercuts could be generated which resulted in high shear strengths. The best set of parameters was found at a laser power of 900 W and a scanning speed of 10,000 mm/s. The shear strength was measured to be 12.5 N/mm², a 25 % improvement compared to previous studies with pw lasers. A further increase of the laser power above 900 W decreased the shear strength of the joint. This is due to the higher energy input rounding the edges of the structures and therefore generating fewer undercuts.

In previous studies the dominant binding mechanism for FPJ was found to be form closure. Thus, the surface pre-treatment has to create a suitable surface. Both analyzed processes generated high undercuts which enabled form closure and could achieve high shear strengths. Regarding process time, the modified RAC process for generating microscopic surface structures was the fastest: an area of 20 cm² was processed within 2.5 s. Surface pre-treatment with pw lasers or with Surfi-Sculpt can take up to several minutes.

Acknowledgment

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