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Thermal joining of thermoplastic metal hybrids by means of mono- and polychromatic radiation

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Abstract

In recent years, joining of plastics and metals for lightweight constructions has become more and more important for industrial applications. This paper presents a novel approach for thermal joining of thermoplastic metal hybrids by means of a combination of mono- and polychromatic radiation. During this work, hybrid joints of aluminum (EN AW-5182) and technical thermoplastics (PC, PA6, PA66-GF30) are studied. Thereby experiments for transmission and heat-conduction joining are performed. Besides, the influences of laser structuring of the metal surface on the joint connections are investigated. Additionally, climate tests according to BMW PR 308.2 from -30°C to 90°C and from -40°C to 120°C are performed to analyze the long-term durability of the hybrid joint connections.

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Keywords: Thermal joining; thermoplastic metal hybrids; mono- and polychromatic radiation

1. Introduction and Motivation

Global warming is a big issue nowadays and needs to be taken seriously. Automobiles contribute at almost a quarter of global CO_2 emissions. It is essential to minimize these emissions to contain the greenhouse effect [1]. Therefore, lightweight constructions are gaining importance in industrial applications [2]. The principle of

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multi-material design is often used to realize the weight reduction. Thereby, for each component the optimum material is selected according to product-specific requirements. This leads to the use of different materials such as steel, aluminum, magnesium and plastics in one vehicle. A major challenge of multi-material design is joining of dissimilar materials [3]. At the moment, there is still a lack of suitable joining techniques which can realize fast and reproducible joint connections of dissimilar materials with high strength. This leads to the conclusion that new joining techniques have to be developed and qualified to solve this problem.

2. Experimental

This paper presents experiments on thermal contour laser joining of thermoplastics and metals in the process variants transmission and heat-conduction joining. The joining process is carried out using the setup shown in Fig. 1 (b). In contrast to the state of the art for laser joining of dissimilar materials [4-15], in this paper two emission beam sources are used. The novel approach combines monochromatic laser radiation (diode laser, cw, λ = 940 nm, $P_{L,max}$ = 70 W, d_L = 4 mm) for joining and additional polychromatic radiation of an infrared emitter (OPTRON IR-Spot, $P_{IR,max}$ = 150 W, d_{IR} = 10 mm) to preheat the joining partners. In 2006 the hybrid welding technology for thermoplastics has been developed by LPKF Laser & Electronics AG in cooperation with the Bayerisches Laserzentrum GmbH. The main advantage of hybrid laser welding compared to conventional laser welding is the volume heating of the upper thermoplastic joining partner which is caused by polychromatic radiation. By this, the thermoplastic stays longer in a molten state which enables a better gap bridging. The additional IR emitter also helps reducing stress in the joint connection by creating a more homogeneous temperature field with lower temperature gradients [16]. Motivated by prior named advantages, in this paper the approach for hybrid laser welding is adapted in order to join thermoplastics to metals by means of a laser and an IR emitter.

Aluminum (EN AW-5182, thickness t = 1.2 mm, width w = 25 mm) and thermoplastics (PC, PA6, PA66-GF30, t = 2.0 mm, w = 25 mm) are used as joining partners. The aluminum surface is laser-structured by a Nd:YAG laser (ns-pulses, λ = 1064 nm, $P_{L,max}$ = 10.5 W, d_L = 40 µm) to improve the adhesion between the joining partners. Two different surface textures (grid and crater structure, see Fig. 1 (a)), each with three different structure depths are realized. The upper aluminum surface is also laser-structured (see Fig. 2 (b) grid structure #3) what improves the absorption of the radiation for heat-conduction joining.

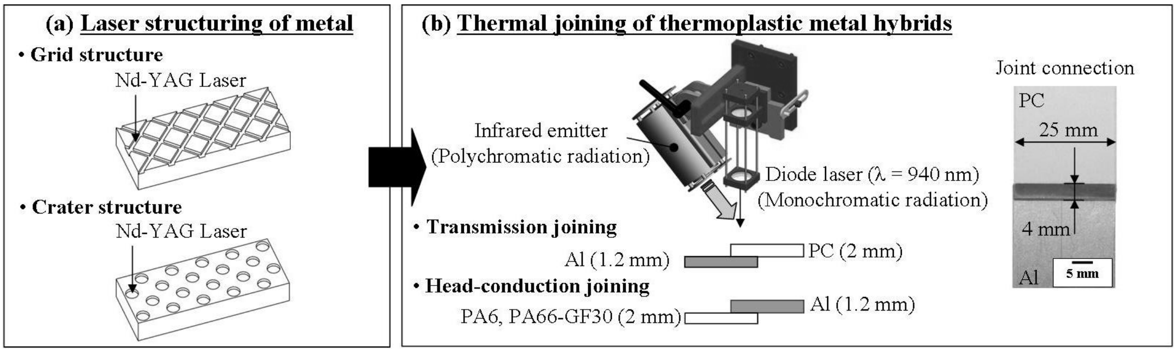

Fig. 1. Experimental setup: (a) Laser structuring of metal; (b) Thermal joining of thermoplastic metal hybrids

The overlap l_o of the specimens is 4 mm (overlap area A = 100 mm). The joined specimens are characterized by microscopy and tensile shear tests whereby the influence of the surface structure (grid, crater) and the thermoplastic joining partner on the tensile shear strength is analyzed. Additionally climate tests according to BMW PR 308.2 are performed in order to investigate the long-term durability of the hybrid joint connections. Two tests are performed with temperature profiles from -30°C to 90°C and from -40°C to 120°C. Each climate test lasts 240 hours and includes 20 cycles. The dwell time at the maximum temperatures is 4 hours whereby the relative humidity varies between 20% for low temperatures and 80% for high temperatures. The switching time between the maxima is 2 hours. The specimens are tested after 20 cycles by means of tensile shear tests and the results are compared with values of unaged samples. The artifical aging of the thermoplastic is analyzed by means of differential scanning calorimetry (DSC). Therefore, PA6 samples are heated and cooled under defined conditions (here: heating / cooling rate = 10°C/min), meanwhile temperature and heat flow associated with thermal transitions in the material are measured.

3. Results and Discussion

3.1. Laser structuring of aluminum

The laser structuring is performed to investigate the influence of different surface structures consisting of craters or grids on the subsequent joining process. Therefore, three different structure depths are considered for each surface structure. They are produced by multiple laser structuring of the surface (number of scans a = 6, 8, 10). The results of laser structuring of aluminum are presented in Fig. 2. The structure depth of the fabricated grids varies between 160 - 200 µm, whereas craters with a high aspect ratio and a structure depth of 200 - 450 µm are realized. In Fig. 2d (# 2, # 3) also a kind of undercuts achieved by laser structuring can be seen. The effects of surface treatment on the hybrid joint connections are shown in the following chapters 3.2 and 3.3.

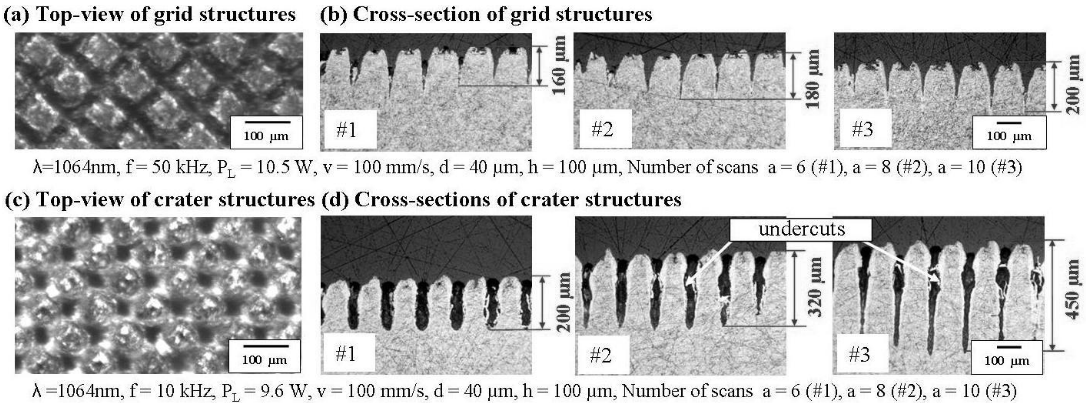

Fig. 2. Results of laser structuring of aluminum: (a) Top-view of grid structures and (b) Cross-section of grid structures with various structure depths; (c) Top-view of crater structures and (d) Cross-section of crater structures with various structure depths

3.2. Transmission joining of polycarbonate to aluminum

The experimental studies for laser transmission joining with mono- and polychromatic radiation show that strong joint connections of polycarbonate and aluminum are possible. The realized tensile shear strength vary from 13.4 MPa to 19.7 MPa (see Fig. 3 (a)). Thereby, the tensile strength for specimens with grid structures are nearly constant and reach values between 15.4 MPa and 16.3 MPa. In contrast to that, the results for specimens with crater structures show a significant influence of the laser structuring parameters on the tensile shear strength of the joint connection. Deep craters in the aluminum surface (see Fig. 2 (d) #2, #3) lead to high tensile shear strength up to 19.7 MPa. However, specimens with small craters cause a low value of

13.4 MPa. A possible solution for this fact can be the mentioned undercuts which are realized by means of laser structuring which enhance the mechanical interlocking between plastic and metal. Moreover, it has to be considered that laser structuring causes a different absorption behavior of laser radiation at the metal surface which leads to a variable temperature distribution and can possibly influence the joining result. By now a clear statement about the best joining parameter cannot be made, but it can be said that comparable or rather higher tensile shear strength can be realized than with conventional hot-melt adhesive (τ = 10 - 15 MPa [17]).

The experiments show no connection between the failure behavior of all PC-Al samples and the laser structuring. The fractures of the hybrid joint connections occur in the area of adhesion between the thermoplastic and the metal (see Fig. 3 (b)). Thereby, the polycarbonate is totally separated from the metal surface. The determined fracture behavior leads to the conclusion that a further optimization of the surface treatment should be possible. An optimum is reached, when a failure of the thermoplastic material in the region of the joint or a substrate fracture occurs.

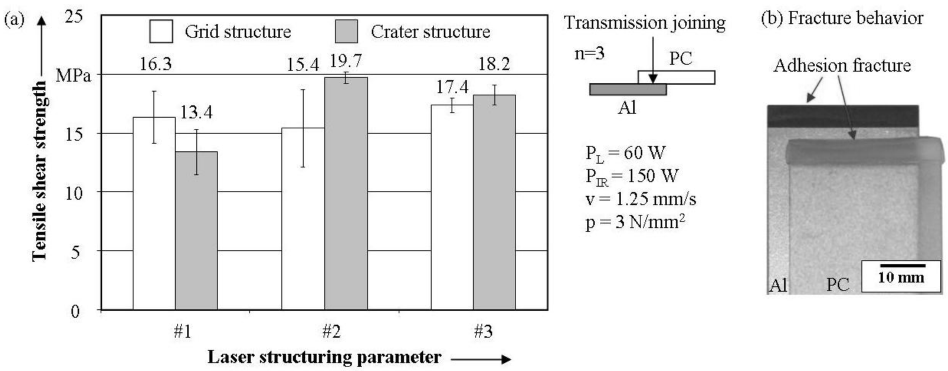

Fig. 3. Results of transmission joining: (a) Tensile shear strength of PC-Al joint connections in dependence on type and depth of surface structure; (b) Fracture behavior of PC-Al joint connection

For a detailed evaluation of the specimen fracture the wetting behavior between polycarbonate and aluminum is analyzed based on cross-section images (see Fig. 4 (b), (c)). The metal surface is totally wetted by the polycarbonate for all specimens with grid structures (see Fig.4 (b)). However, all crater structures still have some air remaining at the bottom of their structures (see Fig. 4 (c)). The remaining amount of air can be explained by the fact, that in contrast to the grid structures, the crater structures have a high aspect ratio and there are no venting channels in which the air can disappear.

By exposing the specimens to climate changes, the tensile shear strength of all specimens significantly decrease (see. Fig. 4 (a)). After the climate test, the tensile shear strength of the samples with grid structures fall from 15.4 MPa to 8.2 MPa. The tensile shear strength of the PC-Al joint connections with crater structure are reduced to a quarter of the reference value. The significant decrease could indicate that remaining air, which expands or compresses depending on temperature, affects the strength of the joint connection. However, it has to be mentioned that the temperature changes of the climate test causes a deformation of the polycarbonate near the joint zone by means of thermal residual stresses (see Fig. 4 (d)). The warpage of the specimens makes it more complicated to fix the brittle polycarbonate in the tensile testing machine without predamaging the joint connection before the actual test occurs. All in all, it is clear that the thermal strain has a negative influence on the mechanical properties of the PC-Al hybrid joint connection.

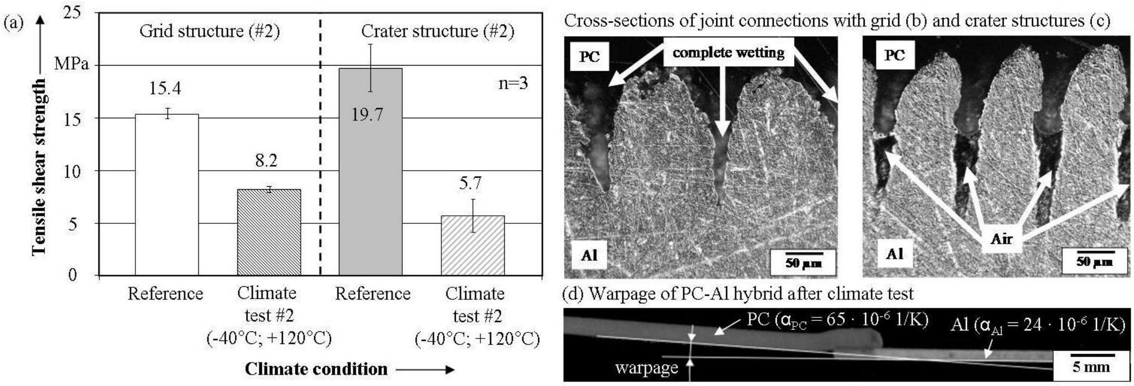

Fig. 4. Results of climate test: (a) Tensile shear strength of PC-Al joint connections (transmission joining) in dependence on climate conditions; (b) Cross-section of a PC-Al joint connection with grid structures; (c) Cross-section of a PC-Al joint connection with crater structures; (d) Warpage of PC-Al hybrid after climate test

3.3. Head-conduction joining of polyamide to aluminum

The joint connections of Al, PA6 and PA66-GF30 are realized by heat-conduction joining. In contrast to transmission joining for heat-conduction joining the optical properties of the thermoplastics are not important. The reason is that the laser radiation is totally absorbed by the metal which further heats the plastic by means of heat-conduction. The upper aluminum surface is also laser-structured (see Fig. 2 (b) grid structure #3) to improve the absorption of the radiation for heat-conduction joining.

The performed experiments demonstrate that heat-conduction joining is a suitable solution for thermal joining of polyamide to aluminum. For all Al-PA6 hybrids with a grid surface structure, nearly constant tensile shear strength between 14.9 MPa and 16.3 MPa (see Fig. 5) are realized, whereby most specimens have a mixed fracture (see Fig. 8 (a)). This means that the used thermoplastics are only partially sheared off and still some thermoplastic residues remain at the metal surface. This statement is also true for samples with crater structures. Their tensile shear strength is in the range of 15.4 MPa and 16.3 MPa. All joined Al-PA6 specimens show only a small variation of tensile shear strength, regardless of type and depth of surface structure. An increase in the tensile shear strength of about 25% in comparison with unreinforced polyamide can be achieved by the use of glass fiber reinforced polyamide (PA66-GF30). Also for Al-PA66-GF30 hybrids the influence of surface treatment on the joint connection cannot clearly be identified because all specimens break in the thermoplastic at about 20 MPa with still intact joint.

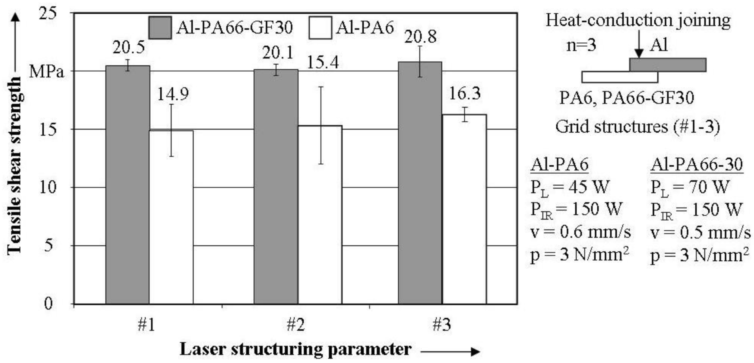

Fig. 5. Results of heat-conduction joining: Tensile shear strength of Al-PA6/-PA66-GF30 joint connections with different grid structures

The filled and unfilled polyamide wets all generated grid structures completely, whereas in the crater structures due to the high aspect ratios similarly to polycarbonate still some air remains in the structure. Regardless of the surface structure in PA66-GF30 a bubble formation near joint zone is detected (see Fig. 6) which does not occur with the other material combinations. This indicates a local thermal decomposition of PA66-GF30 which is caused by to much energy. In future investigations, the process window will be examined in more detail so that material damage can be avoided.

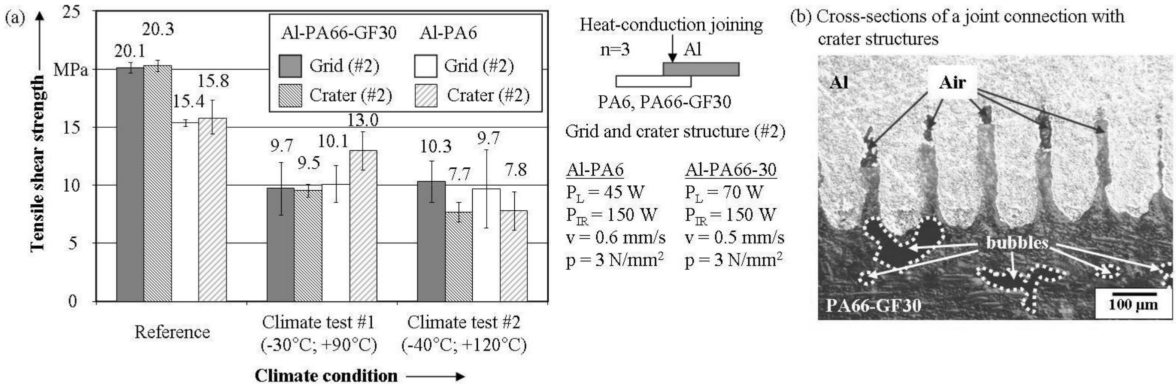

Fig. 6. Results of climate test: (a) Tensile shear strength of Al-PA6/-PA66-GF30 joint connections with grid and crater structures in dependence on climate conditions; (b) Cross-section of a Al-PA66-GF30 joint connection with crater structures;

The climate test causes also a slightly deformation of the polyamide. However the warpage is much lower than for polycarbonate. Compared to the brittle polycarbonate, polyamide is a tough material so that small thermal deformation plays a subordinate role and can be neglected. After the climate tests, the tensile shear strength of all Al-PA6 hybrids decreased. The values for specimens with grid structures decreased by one-third from 15.4 MPa to 10.1 MPa (cycle: -30°C to 90°C) and to 9.7 MPa (cycle: -40°C to 120°C). The tensile shear strength of specimens with crater structures drops from 15.8 MPa to 13.0 MPa (cycle: -30°C to 90°C) and to 7.8 MPa (cycle: -40°C to 120°C). Moreover, the tensile shear strength of PA66-GF30 specimens are reduced by half from 20.11 MPa to 9.68 MPa (cycle: -30°C to 90°C) and to 10.32 MPa (cycle: -40°C to 120°C). Samples with craters show a similar behavior. This means that after climate test #1, most of the samples reached values between 10 MPa and 13 MPa, whereas after climate test #2 only values between 7 MPa and 10 MPa are measured

Besides a yellowing of the samples after the climate test, also a shift of the characteristic temperatures is detected by means of DSC. In Fig. 7 it is shown that for PA6 the melting temperature drops slightly after the climate tests and the crystallization temperature increases significantly. Due to literature [18] this behaviour is typical for a chemical degradation of plastic. The melting temperature drops because of lower crystal perfection caused by oxidation and the crystallization temperature increases caused by a nucleation. Typical aging effects such as yellowing due to oxidation, micro-cracking and deterioration of mechanical properties occur if polyamide is longer used at temperatures above 70°C (Climate test: temperatures of up to 90°C / 120°C) in presence of oxygen. Due to moisture (Climate test: 80% moisture at 90C / 120°C and 20% moisture at -30°C / -40°C) the thermal-oxidative degradation is accelerated [18]. These results lead to the conclusion that the thermoplastics samples are artificially aged during the climate test. The decrease of the mechanical properties is most likely caused by physical and chemical aging of the thermoplastic.

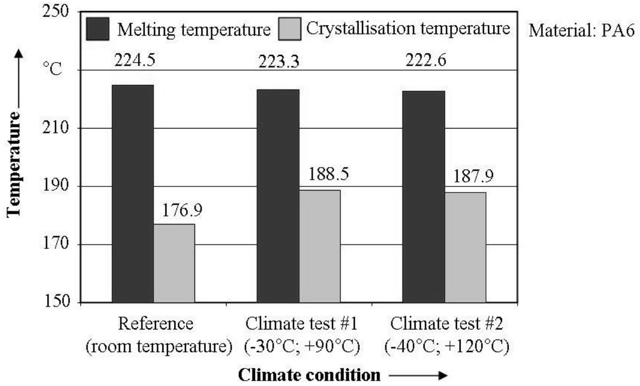

Fig. 7. Results of climate test: Characteristic temperatures of PA6 in dependence on climate conditions measured by means of DSC

After the climate test, no clear statement about the fracture behavior of Al-PA6 is possible because alternately adhesion, mixed and substrate fractures occured (see Fig. 8 (c)-(e)). Due to thermal stress, the fracture type for PA66-GF30 completely changes. After the climate test, all PA66-GF30 specimens cohesively fail near the joint zone where the bubbles are located (see Fig. 6 (b)). Fig. 8 (f) shows that after the fraction a slight thermoplastic layer still remains on top of the aluminum surface. This leads to the conclusion that the adhesion of the thermoplastic material to the aluminum is very good and the fracture is caused by the bubbles.

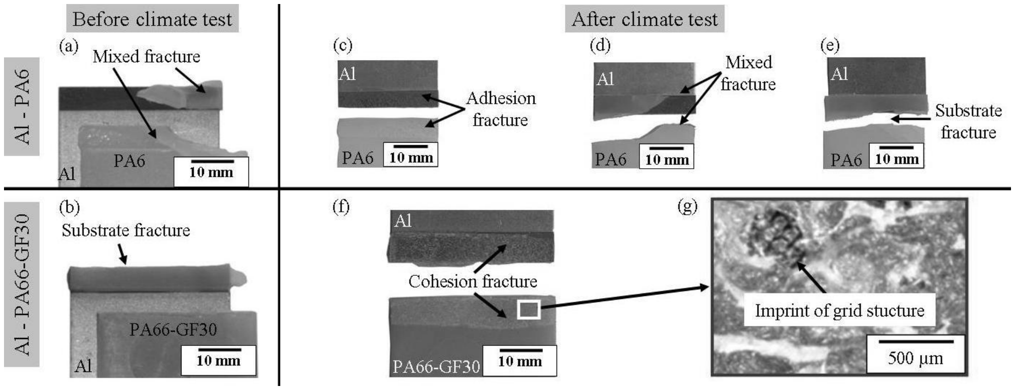

Fig. 8. Results of climate test: Top-view of fractures of polyamide - metal hybrids before (a)-(b) and after (c)-(g) climate test

4. Conclusion and outlook

The use of tailored multi-material components which consist of thermoplastics and metals are gaining in importance in the next few years because of their high potential for weight reduction. However, at the moment there is a lack of suitable techniques for the joining of dissimilar materials. Therefore new joining techniques have to be developed and qualified to solve this problem.

In this paper a novel approach for joining thermoplastics to metals by means of a combination of mono- and polychromatic radiation is presented. Thereby experiments on thermal contour laser joining of technical thermoplastics (PC, PA6, PA66-GF30) and aluminum (EN AW-5182) with various surface structures (grids, craters) in the process variants transmission and heat-conduction joining are performed. The experiments show that strong joint connections of thermoplastics and metals are possible. For transmission joining of PC-Al hybrids, tensile shear strength of up to 19.7 MPa are reached. Thereby the tensile shear strength for specimens with grid structures reach constant values of about 16 MPa. Specimens with crater structures confirm an influence of the laser structuring parameters on the tensile shear strength. Their values vary from 13.4 MPA to 19.7 MPa. One reason for this could be a better mechanical interlocking of the thermoplastic with deep crater structures with undercuts. However it has to be mentioned that all crater structures have still some air remaining at their bottom which seems to influence the tensile shear strength after the climate test.

The reached tensile shear strength for Al-PA6 hybrids made by heat-conduction joining are in the range of 15.4 and 16.3 MPa. The specimens show only a small variation of tensile shear strength, regardless of type and depth of surface structure. An increase in tensile shear strength of about 25% can be achieved by the use of glass fiber reinforced polyamide (PA66-GF30) instead of unforced PA6. For Al-PA66-GF30 hybrids the influence of surface treatment on the joint connection can also not clearly be identified because all specimens break in the thermoplastic at about 20 MPa whereby the joint is still intact. Regardless of the surface structure in PA66-GF30, a bubble formation near the joint zone is detected which additionally affects the mechanical strength of the connection after climate test.

After the climate tests, the tensile shear strength of all thermoplastic metal hybrids decreased. The reason therefore is the aging of the thermoplastics. After climate test #1 (cycle: -30°C to 90°C) the polyamide samples reached values between 10 MPa and 13 MPa, whereas after climate test #2 (cycle: -40°C to 120°C) only values between 7 MPa and 10 MPa are measured. The tensile shear strength of PC-Al hybrids dropped to 8.2 MPa (climate test #1) and to 5.7 MPa (climate test #2). The experiments show that the mechanical strength of the joined hybrids highly depends on the properties of the thermoplastic and its aging behavior.

The reported experiments demonstrate that the new approach is a suitable solution for thermal joining of dissimilar materials. Further investigations will be performed to answer the question if it is possible to join dissimilar materials without laser surface treatment by this new approach. Besides, tests will be performed with lasers and infrared emitters with more power in order to increase the joining speed and the strength.

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