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ScienceDirect
Physics Procedia 56 (2014) 824 – 834
Physics Procedia

8th International Conference on Photonic Technologies LANE 2014

Experimental Investigations of Thermal Joining of Polyamide Aluminum Hybrids Using a Combination of Mono- and Polychromatic Radiation

Philipp Amend[a,*], Christian Mohr[a], Stephan Roth[a,b]

[a]*Bayerisches Laserzentrum GmbH (blz), Konrad-Zuse-Str. 2-6, 91052 Erlangen, Germany*
[b]*Erlangen Graduate School in Advanced Optical Technologies (SAOT), Friedrich-Alexander-Universität Erlangen-Nürnberg, Paul-Gordan-Str. 6, 91052 Erlangen, Germany*

Abstract

In recent years, the joining of plastics and metals for lightweight constructions has become more and more important for industrial applications. This paper presents experimental investigations of transmission joining of polyamide aluminum hybrids using a combination of mono- and polychromatic radiation. The used experimental setup consists of a diode laser, a laser processing head with additional infrared emitters, a robot and a clamping device for lap joints. With this setup, experiments are performed to determine a process window for the thermal joining of polyamide aluminum hybrids and to evaluate geometrical, material-related and process-related limits of the approach. For that, hybrid joints of aluminum with sheet thicknesses of 0.6 mm to 1.0 mm and 3 mm thick unfilled polyamide 6 are used. To improve the mechanical interlocking between the polyamide and the aluminum surface a prior laser structuring of the metal is done by a ns-Nd:YAG-laser. Primarily, the influence of surface roughness and surface enlargement on the optical properties of aluminum and the mechanical properties of the joined specimens is investigated.

Peer-review under responsibility of the Bayerisches Laserzentrum GmbH
Keywords: Thermal joining; thermoplastic metal hybrids; mono- and polychromatic radiation

* Corresponding author. Tel.: +49-9131-97790-28 ; fax: +49-9131-97790-11 .
E-mail address: p.amend@blz.org

Peer-review under responsibility of the Bayerisches Laserzentrum GmbH
doi:10.1016/j.phpro.2014.08.098

1. Introduction and state of the art

In future, the use of tailored multi-material components consisting of thermoplastics and metals will increase in the field of automotive and mechanical engineering based by the pursuit of lightweight design and efficiency of resources. This provides completely new demands on automated manufacturing because dissimilar materials have to be joined reliably.

The joining of thermoplastic metal hybrids is already realized by In-Mold Assembly (IMA) and Post-Mold Assembly (PMA) processes. The IMA processes can be divided into insert, outsert and hybrid technology. Typical for IMA processes is that a metal component is positioned into a mold and combined with thermoplastic material during a primary shaping process like for example injection molding (Flock 2011). For PMA processes the joining takes place after the production of semi-finished products, so that a higher geometrical complexity of the parts can be realized in contrast to IMA processes. In this case, a division into mechanical, chemical and thermal methods is common. Currently, the mix of materials is mainly realized by bonding or mechanical joining. However, these methods have disadvantages such as a large number of process steps or extra weight by connecting elements (Neitzel 2004, Ehrenstein 2006).

A promising approach is the thermal joining by laser radiation which enables a non-contact, automated and reproducible production of thermoplastic metal hybrids. Thereby, laser radiation heats the metal and through heat conduction the thermoplastic melts and wets the metal surface. To improve the mechanical interlocking between the thermoplastic and the metal surface often a prior laser structuring of the metal is used. After cooling, the dissimilar materials are joined together.

Since the development of direct laser joining for metal and plastics in 2006 (Katayama 2006, Kawahito 2006) several studies have been performed to improve thermal joining of dissimilar lightweight materials. In contrast to the state of the art for laser joining of dissimilar materials in this paper two emission sources are used. This approach is based on the assumption that because of the different thermo-physical properties of thermoplastics and metals a tailored heating is necessary for achieving optimal joint connections. In 2006 the hybrid welding technology for joining thermoplastics with a combination of mono- and polychromatic radiation 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 infrared emitter also helps reducing stress in the joint connection by creating a more homogeneous temperature field with lower temperature gradients (Hofmann 2006). Motivated by prior named advantages, the approach for hybrid laser welding is adapted in order to join thermoplastics to metals. The first experiments using this approach for joining thermoplastic metal hybrids were done by the authors in 2013 (Amend 2013) and show that this approach can be used for joining dissimilar materials as well. However, the former used setup included a low power diode laser ($\lambda = 940$ nm, $P_{L,max} = 70$ W, $d_L = 4$ mm) and a low power infrared emitter (OPTRON IR-Spot, $P_{IR,max} = 150$ W, $d_{IR} = 10$ mm) so only a process velocity of about 1 mm/s was reached. Besides the low process velocity, there is still a need for research on the influence of surface structures on the joining process and the resulting joint connection.

2. Objective and approach

In this paper an experimental setup consisting of a diode laser (Trumpf TruDiode 351), a laser processing head with additional infrared emitters (LPKF TwinWeld3D), a robot (Kuka KR 16) and a clamping device are used to join polyamide aluminum hybrids by combined mono- and polychromatic radiation. During the joining experiments the parameters laser power P and velocity v are varied to determine a process window for thermal joining of polyamide aluminum hybrids. Thereby, geometrical, material-related and process-related limits of the approach are investigated. In addition, the influence of a prior laser structuring of the aluminum surface on the joint connections is studied. Therefore, the surface is line-patterned, wherein the structure distance s and the structure depth d are varied.

3. Materials and setup

3.1. Materials

This paper presents experiments on thermal contour joining of thermoplastics and metals in the process variant transmission joining. Therefore 3 mm thick unfilled polyamide 6 (Tecamid 6) and aluminum (AlMg3) with sheet thicknesses of 0.6 mm, 0.8 and 1.0 mm are used. The dimensions of all specimens are 120 mm · 50 mm. The specimens are fixed in a clamping device with an overlap length l_o of about 5 mm and joined under pressure. Afterwards, the fabricated lap joints are cutted into specimens for tensile shear tests (length l = 95 mm, width w = 25 mm). In Tab. 1 the most important properties of the used materials are summarized.

Table 1. Relevant material properties of polyamide and aluminum used (Ensinger 2013, Hesse 2010).

material properties	unit	PA 6	AlMg3
density	kg / m^3	1140	2660
E-modulus	MPa	1800	70500
tensile strength	MPa	79	190 - 250
melting temperature	° C	221	610 - 640
thermal conductivity	W / (m · K)	0.37	140 - 160

The material thickness of the aluminum sheets is varied to investigate the influence of different bending stiffnesses on joint connections. The bending stiffness can be calculated using equation shown in Fig. 1 (b). Thereby, E is the E-modulus of the material, w the specimen width and t the material thickness. Fig. 1 (a) shows the bending stiffnesses for polyamide 6 and aluminum for different material thicknesses. In order to equalize the bending stiffness of aluminum to 3.0 mm thick polyamide (calculated with E_{PA6} = 1800 MPa), a material thickness of 0.88 mm is necessary. However, a material thickness of 0.9 mm is not common, so that material thicknesses of 0.8 mm and 1.0 mm are used. Besides the bending stiffness, the variation of material thickness has to be analyzed according to heat losses through the aluminum specimen during the joining process and its influence on the joint connection. It is assumed that due to the high thermal conductivity of aluminum (see Tab. 1) and in dependency of material thickness a certain amount of energy dissipates from the joining zone and is lost for the joining process.

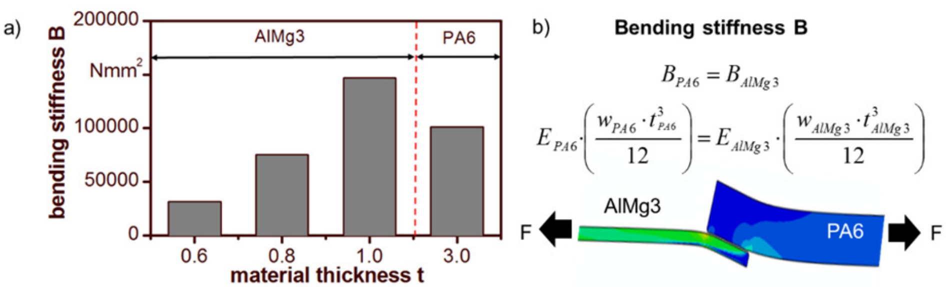

Fig. 1. (a) Bending stiffness B for various material thicknesses and materials; (b) Calculation of bending stiffness B and schematic illustration of specimen deformation during tensile shear test.

3.2. Laser structuring of aluminum

The laser structuring of aluminum is performed to investigate the influence of different defined surface structures (see Fig. 2) on the joint connections. Therefore, the surface of the AlMg3 samples are partially laser-structured by means of a ns-Nd:YAG-laser (Trumpf VMC3) to improve the laser absorption of AlMg3 during the joining process and to cause a larger effective joining area which should enhance the mechanical interlocking between the joining partners.

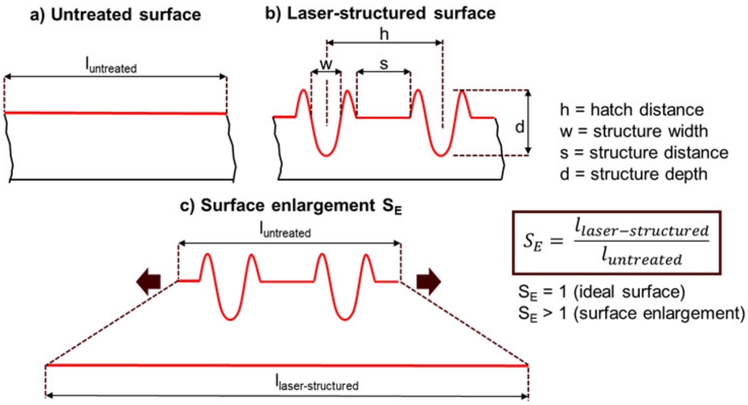

Fig. 2. (a) Untreated surface; (b) Laser-structured surface and relevant parameters; (c) Schematic illustration and definition of surface enlargement S_E.

The line-patterned surface is defined by the used hatch distance h, the structure distance s, the structure width w and the structure depth d (see Fig. 2). The hatch distance is the distance between two lines. It is varied between 80 µm and 120 µm. The structure distance is defined by the length of untreated surface between two lines. The structure width w is about 30 to 35 µm and is chosen as factor to determine the structure distance s (s = 2 · w; s = w and s = w/2). Besides, the structure depth d is varied between 25 µm ± 5 µm and 50 µm ± 5 µm. Relevant laser structuring parameters are shown in Tab. 2.

Table 2. Relevant laser structuring parameters.

structure distance s [-]	structure depth d [µm]	laser power P [W]	frequency f [kHz]	velocity v [mm/s]	hatch distance h [µm]	number of scans n [-]
2 · w	50	10.8	40	300	120	4
w	50	10.8	40	300	100	4
w/2	50	10.8	40	300	80	4
w/2	25	10.8	40	300	80	2

In order to characterize the different laser-structured surfaces with respect to their optical properties, spectrometric measurements are carried out (spectrophotometer Shimadzu UV-3600). Thereby, the reflection of the aluminum surface for wavelengths from 300 up to 2000 nm is measured. Taking into account that no transmission is present for metals, the absorption can be calculated (Absorption A = 1 - Reflexion R).

3.3. Experimental setup for thermal joining

The joining process is carried out using a setup consisting of a diode laser (Trumpf TruDiode 351), a laser processing head with additional infrared emitters (LPKF TwinWeld3D), a robot (Kuka KR 16) and a clamping device for lap joints. The samples are positioned on the aluminum carriage of the clamping device, whereby an insulating intermediate layer is used to prevent a high heat flow into the clamping device. At the beginning of the joining process, the specimens are preheated for a short time (t_{wait}) just by the use of laser radiation. After the waiting time, the robot moves the processing head across the clamped specimens and the joint connection is formed. Relevant process parameters are listed in Tab. 3.

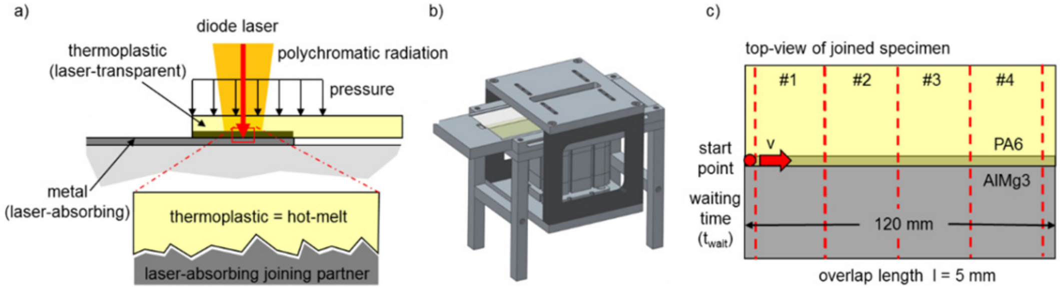

Fig. 3. (a) Schematic illustration of thermal joining of thermoplastic metal hybrids using a combination of mono- and polychromatic radiation; (b) CAD illustration of the used clamping device; (c) Top-view of used specimens which are cutted into four pieces after joining.

Table 3. Relevant laser joining parameters.

parameter set	laser power P [W]	laser focus diameter d [mm]	infrared emitter power P_{IR} [W]	waiting time t_{wait} [s]	velocity v [mm/s]
parameter set 1	156.6	5	1000	1.8	3/4/5
parameter set 2	203.0	5	1000	1.9	11/12/13/14/15

3.4. Characterization of specimens

All joined specimens are characterized by tensile shear tests to analyze the influence of the surface structures and the process parameters laser power and velocity on the breaking. Besides, microscopy images of the joint connections are prepared to investigate the process and material related wetting length. According to the wetting behavior conclusions on the temperature fields, the energy input during the joining process and the mechanical interlocking between the dissimilar materials can be done. After the tensile shear test, the fracture surfaces are also characterized in terms of their fracture behavior. Especially, adhesion/mixed fractures and material fractures are detected (see. Fig. 4 (b)).

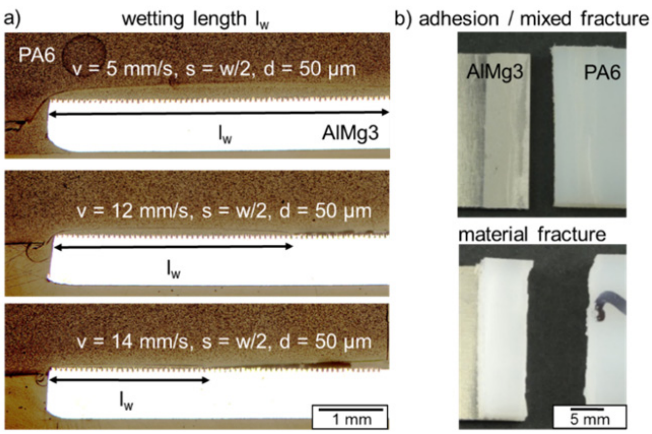

Fig. 4. (a) Micrographs of joint connections with different wetting lengths l_w according to velocity v; (b) Top-view of tested joint connections with different fracture behaviors.

4. Results and discussion

4.1. Influence of laser structuring on surface structure and optical properties of aluminum

In Fig. 5 laser scanning microscope (LSM) images (Fig. 5 (a-d)) and micrographs (Fig. 5 (e-h)) of the laser-structured aluminum surfaces are shown. Based on the LSM images, the arithmetic mean surface roughness R_a is calculated. The surface enlargement S_E is measured as shown in Fig. 2. Both results are presented in Fig. 6. It can be stated that the roughness and the surface enlargement increase with deeper structure depths and lower structure distances.

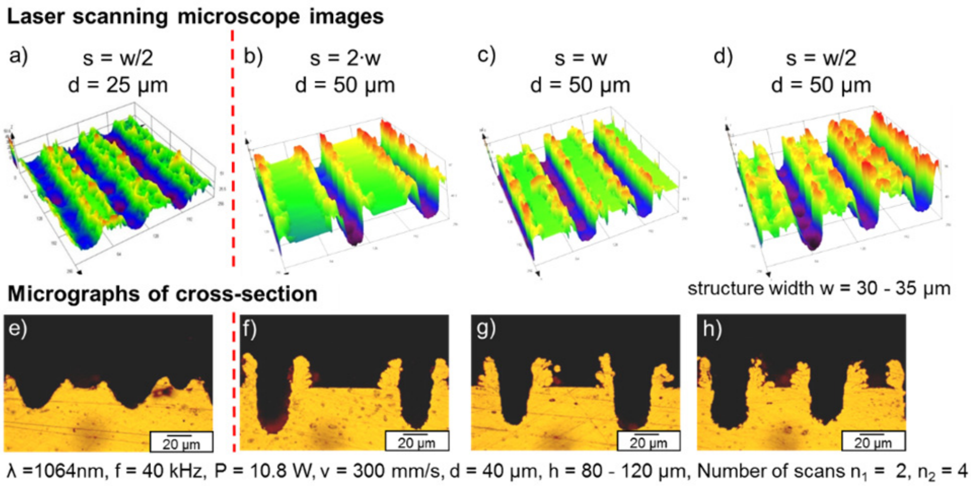

Fig. 5. (a-d) Laser scanning microscope (LSM) images and micrographs (e-h) of various aluminum surfaces in dependency of structure distance s and structure depth d.

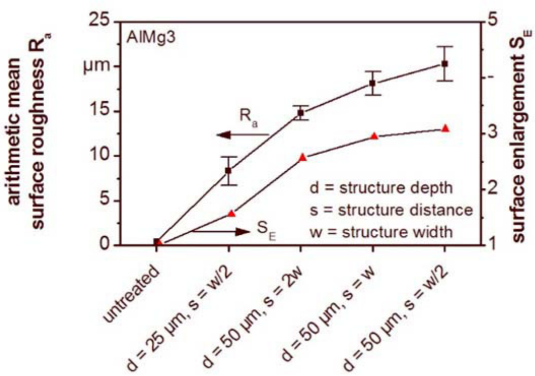

Fig. 6. Arithmetic surface roughness R_a and surface enlargement S_E of various aluminum surfaces in dependency of structure distance s and structure depth d.

According to spectrometric analysis an assessment of the measured reflection and the calculated absorption is possible (Absorption A = 1 - Reflection R, with Transmission T = 0). It appears that the untreated aluminum surface is highly reflective (see Fig. 7 (a-b)). However, the absorption increases with a decreasing structure distance. For surfaces being defined by s = w and s = 2 · w the absorption reaches slightly higher values than for the untreated surface (see Fig. 7 (a)). However, these surfaces have still some untreated areas (see Fig. 5 (f, g)) which are responsible for a high reflection. For a structure distance s = w/2 almost the whole surface is modified by laser structuring and therefore a higher absorption occurs. For the surface with a structure depth of 50 µm higher absorption values are obtained than for the surface with a structure depth of 25 µm (see Fig. 7 (b)). A probable reason is the enlargement of the surface, whereby multiple reflections in the deeper cavities are possible.

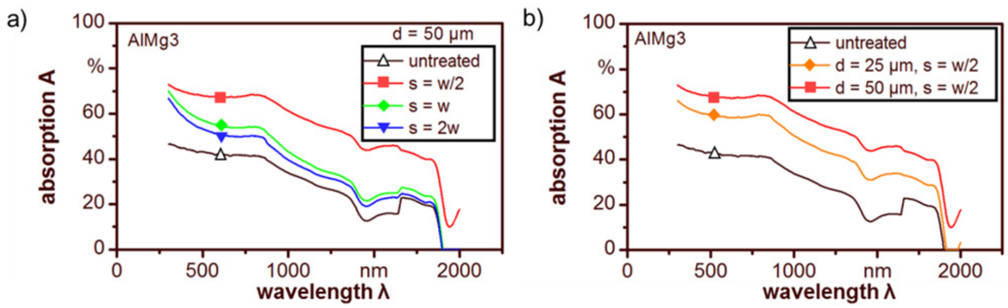

Fig. 7. (a) Spectral absorption A of various aluminum surfaces in dependency on structure distance s; (b) Spectral absorption A of various aluminum surfaces in dependency on structure depth d.

4.2. Influence of structure distance on joint connection

The investigations show that the structure distance s has a significant influence on the joining results. Considering specimens joined with parameter set 1 (see Tab. 3) it is clear that for low velocities (v = 3 - 5 mm/s) an approximately constant wetting length l_w in the range of 5.1 to 5.6 mm is obtained (see Fig. 8 (b)). However, the measured values of the breaking forces show that at approximately the same wetting length higher breaking forces for specimens with a structure distance s = w/2 ($F_{B,v = 3\ mm/s}$ = 3167.8 N; $F_{B,v = 4\ mm/s}$ = 3272.7 N; $F_{B,v = 5\ mm/s}$ = 3051.2 N) compared to the specimens with structure distance s = w ($F_{B,v = 3\ mm/s}$ = 2918.8 N; $F_{B,v = 4\ mm/s}$ = 2934.1N; $F_{B,v = 5\ mm/s}$ = 2800.8 N) and s = 2 · w ($F_{B,v = 3\ mm/s}$ = 2484.1 N; $F_{B,v = 4\ mm/s}$ = 2615.1 N; $F_{B,v = 5\ mm/s}$ = 2291.3) can be achieved (see Fig. 8 (a)).

Almost all samples break in the plastic part. This fracture behavior is known for thermoplastic metal adhesive bonds that are tested in the tensile shear test. In (Rasche 1986) it is described that the cause of this fracture behavior is a multi-axis inhomogeneous loading condition in the sample. The tensions in the sample are mainly determined by the deformation behavior of the joining partners and their geometry. The macroscopic part geometry and the overall deformation behavior of the aluminum and the polyamide is the same for all samples. However, the different metal surfaces and the realized mechanical interlocking between plastic and metal influence the flux of force according to the structure distance. By deflection of the flux of force a notch effect in the plastic as well as the metal part is created. It can be concluded that there is a better flux of force between the two materials and also lower tensions at the end of the plastic samples occur for structure distance s = w/2 (see Fig. 8 (a)). This behavior leads to material fractures at higher breaking forces. For the samples that are joined with higher velocities (v = 11 - 15 mm/s, see parameter set 2, Tab. 3) can be clearly seen that with increasing velocity the wetting length decreases. In addition, the investigations show that the structure distance has an effect on the absorption (see Fig. 7 (a)), and thus the available process energy which is responsible for the wetting length. With decreasing wetting length the breaking force decreases. The fracture behavior of the samples differs depending on the structure distance. Joint connections with a structure distance of s = w/2 show mainly material fractures in the plastic part, whereas starting at velocity of v = 12 mm/s and higher most of the samples with a structure distance of s = w and s = 2 · w have mixed/adhesive fractures (see Fig. 8 (c)).

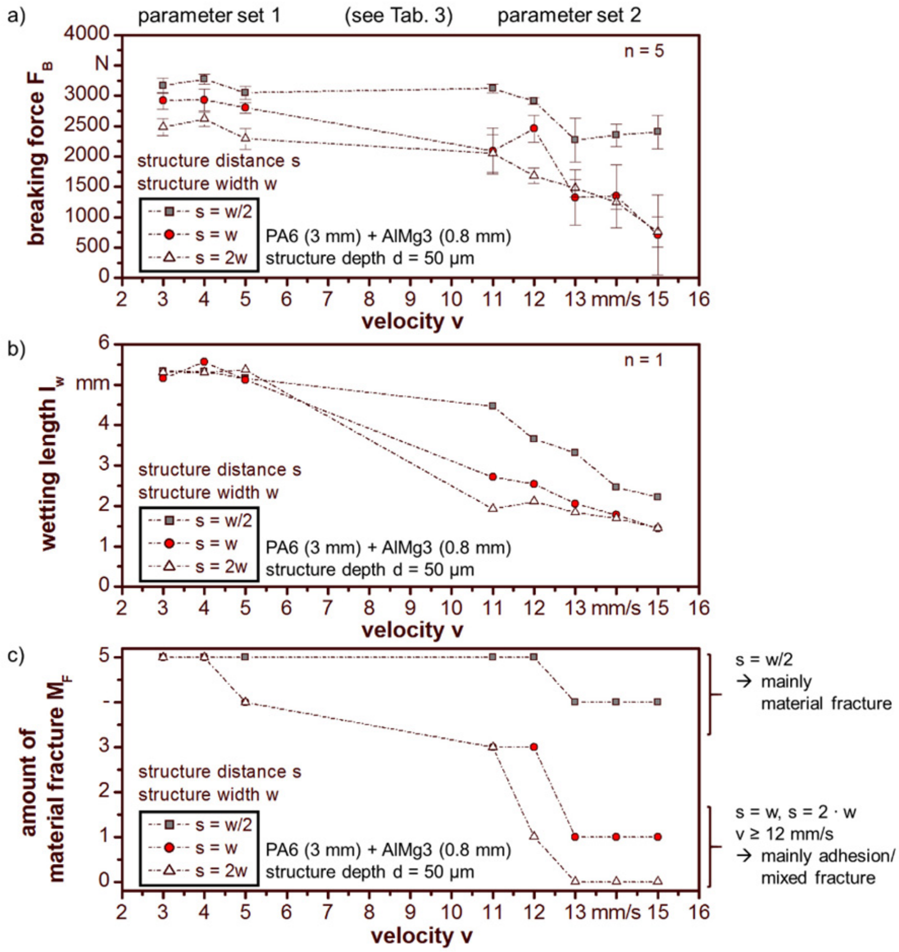

Fig. 8. (a) Breaking force F_B, (b) wetting length l_w, (c) amount of material fractureM_F in dependency of velocity v for polyamide aluminium hybrids with various structure distances s.

4.3. Influence of structure depth on joint connection

In addition to the variation of the distance, experiments are conducted in which the structure depth d is varied. The samples are joined with a constant laser and infrared emitter power (P = 203 W, P_{IR} = 1000 W, further parameters see Tab. 3 parameter set 2), wherein the velocity is changed in the range of 11 to 15 mm/s. It is shown that the structure depth has an impact on the achievable breaking force. Thereby, slightly higher values for structure depths of 50 µm are observed in comparison to structure depths of 25 µm. This can be explained by the fact that a surface enlargement (see Fig. 6) allows a better flux of force and a better tension distribution. Fig. 9 (b) shows that the wetting length decreases with increasing velocity and moderately lower wetting lengths for samples with a structure depth of 25 µm are achieved, because absorption on the aluminum surface is slightly lower than for samples with 50 µm structure depth (see Fig. 7 (b)). When considering the fracture behavior it is clear that up to a velocity of 12 mm/s always material fractures in the plastic parts takes place. However, with increasing velocity the amount of adhesion/mixed fractures rises.

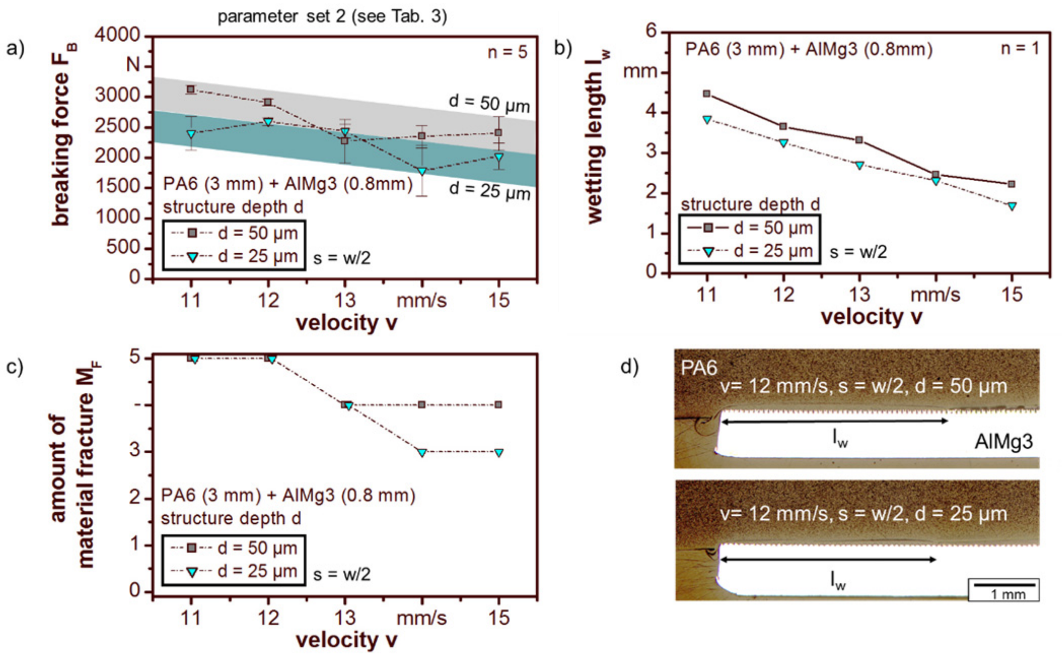

Fig. 9. (a) Breaking force F_B, (b) wetting length l_w, (c) amount of material fracture M_F in dependency of velocity for polyamide aluminium hybrids with various structure depths d; (d) Micrographs of joint connections with different structure depths d.

4.4. Influence of material thickness on joint connection

It is known that the strength and deformation behavior of the joining partners determines the occurrence of stress concentration in adhesive bonds (see Rasche 1986). This must also be considered for thermal joining. For this purpose the material thickness of the aluminum specimens are varied and thus produces different stiffnesses (see Fig. 1 (a, b)). Moreover, the thickness of the aluminum sample affects the actual joining process, because of the fact that energy is dissipating into the material. This effect becomes particularly clear looking at Fig. 10 (b). The wetting length decrease with increasing material thickness because energy dissipates in the metallic joining partner and is no longer available for melting the thermoplastic. The analysis of the breaking forces and the fracture behavior in this case requires a more detailed look on the deformation behavior of the samples. In Fig. 10 (d), therefore, typical fracture and deformation modes are shown as a function of the material thickness. It is clear that for small sheet thickness of 0.6 mm there is a strong bending (α = 19°) of the metallic joining partner. Bending leads to peeling stress within the joint connection (Rasche 1986), which in this case causes that the plastic shears off. In contrast to specimens with small sheet thicknesses, for thicker sheets (t = 0.8 or 1.0 mm) primarily material fracture of the plastic component occurs. Even thicker parts show a deformation (see Fig. 10 (d)) in the range of 10 to 15 degrees. However, the peeling stress is not sufficient to shear off the plastic. Because of the fact that thin samples have an almost constant wetting length which is independent form the velocity (t = 0.6 mm, v = 11 - 15 mm/s), the breaking forces are almost unchanged and reach values about 3000 N. Samples with higher material thickness show a decrease in breaking force which correlates with the decrease in the wetting length caused by heat losses.

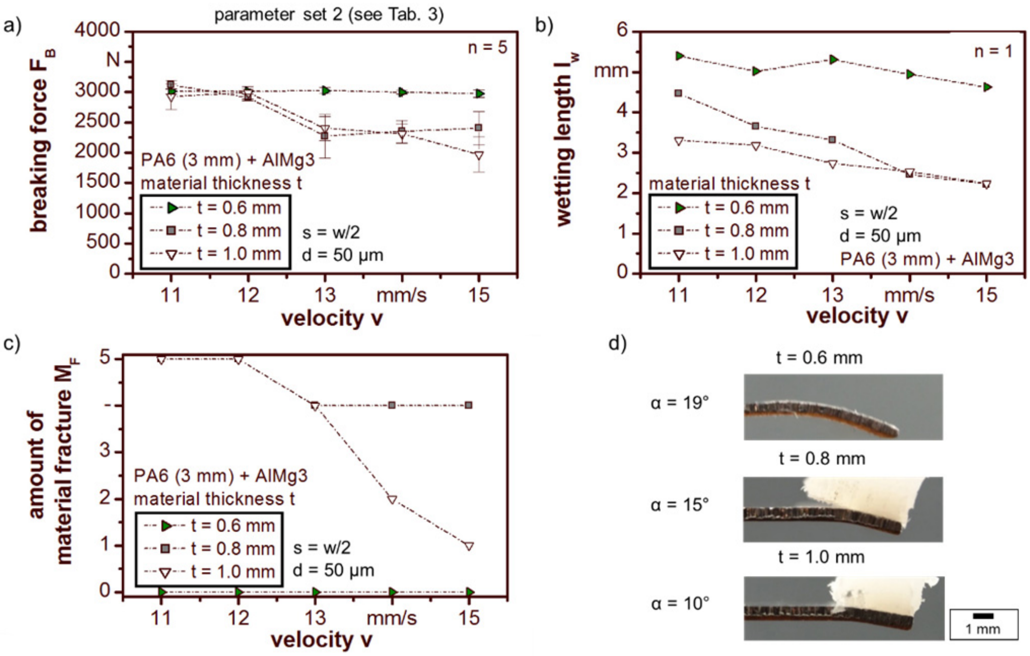

Fig. 10. (a) Breaking force F_B, (b) wetting length l_w, (c) amount of material fracture M_F in dependency of velocity v for polyamide aluminium hybrids with various material thicknesses t; (d) Deformation of polyamide aluminium specimens in dependency of metal sheet thickness t.

5. Conclusion and outlook

The use of thermoplastic metal hybrids is gaining in importance motivated by lightweight design and efficiency of resources. Therefore, reliable joining techniques are needed which fulfill the demands of the dissimilar materials and on automated manufacturing. In this paper, the latest results for joining thermoplastics to metals by means of a combination of mono- and polychromatic radiation are presented. Thereby, experiments on thermal contour joining of polyamide 6 (PA6) and aluminum (AlMg3) with various surface structures in the process variant transmission joining are performed. The experiments show that a fast fabrication of strong joint connections of thermoplastics and metals is possible. Thereby, the pretreatment of the aluminum surface by means of laser structuring plays an important role. It is shown that the optical properties of the aluminum as well as the mechanical properties of the joint connections depend on the realized surface structure. Besides, the material thickness of the joining partners affects the joint connection because of its influence on heat transfer during the joining process and the deformation behavior of the joined specimens. All in all, the reported experiments demonstrate that the approach has high potential to complement established joining processes in the field of automotive and mechanical engineering and to promote the use of multi-material components for lightweight applications. Future investigations will be performed to realize load-optimized surface structures to further improve the joint connections.

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