Lasers in Manufacturing Conference 2017

Investigations on laser-based hot-melt bonding of additive manufactured plastic parts to metal sheets for strong and tight multi-material joints

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Abstract

In this paper, first results regarding the realization of laser-based hot-melt bonding of additive manufactured plastics parts to metal sheets for strong and tight multi-material joints are presented. Compared to earlier investigations, in which nearly solely extruded plastic materials were applied, the use of additive manufactured plastics complements the research field with a promising approach. Besides the typical advantages of multi-material joints regarding weight reduction and high strengths, such parts can meet the needs of constructional freedom and the avoiding of tool costs. Materials used for this paper are aluminum (AlMg3), stainless steel (1.4301) and polyamide 12 (PA12). The performed experiments resulting in multi-material joints between metal and polyamide. The realized specimens undergo a tensile shear test and a tightness test, in which the characteristics of the joints are determined.

Keywords: Laser-based hot-melt bonding; multi-material joint; additive manufacturing

1. Introduction

In previous years, the use of Additive Manufacturing (AM) in industry has increased significantly [Petrovica, et al., 2011.]. AM processes enable the direct generation of complex geometries which are hardly machinable with conventional technologies based on CAD data without any shape forming tools. However, up to now powder-bed-based AM technologies for plastics, like selective laser sintering, are limited to a single material during the industrial production process. Although there are new technologies for the direct

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generation of multi-material parts [Stichel, et al., 2015], this implies the need for suitable joining techniques to combine additive manufactured plastic parts with other materials, such as metals, to gain tailored multi-material components. A promising approach is the laser-based hot-melt bonding of thermoplastic metal hybrids, whereby a fast, flexible and non-contact joining without the use of an additional adhesive is possible [Amend et al., 2016]. In the first process step, laser radiation warms the metallic joining partner. By heat conduction from the metallic joining partner towards the plastic, the melting temperature of the thermoplastic joining partner is locally reached in the contact zone. The molten plastic subsequently adheres to the metal surface by wetting and after cooling a durable joint between both materials is formed (see Fig. 1).

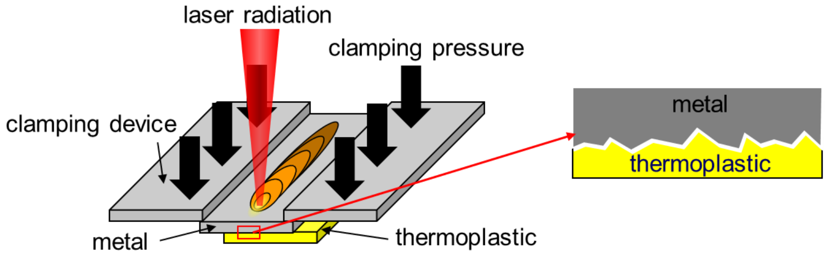

Fig. 1. Schematic illustration of laser-based hot-melt bonding of metal plastic hybrids

2. Objectives and experimental setup

In this paper, experimental investigations are performed to achieve an improved understanding of laser-based hot-melt bonding of additive manufactured plastic parts to metal sheets for strong and tight multi-material joints. For the joining process, a setup consisting of a disc laser (P_{max} = 4 kW, λ = 1030 nm), a scanner optic (f = 450 mm), a robot and a clamping device is used (see Fig. 2). The thermoplastic metal hybrids are realized by heat-conduction joining. In contrast to transmission joining, which is due to the optical properties of additive manufactured PA12 not applicable, during heat-conduction joining the laser beam directly irradiates the metal, with the plastic part placed below. The radiation is totally absorbed at the metal surface and further the polyamide melts through heat conduction (see Fig. 1).

In the experiments, stainless steel (1.4301, 50 50·1 mm^3) or aluminum (AlMg3, 50 50·1 mm^3) are joined with unfilled polyamide 12 (PA12). Stainless steel and aluminum are often used for industrial applications. Stainless steel is characterized by a significantly improved corrosion resistance against unalloyed steels [Henkel, G., 2008]. Aluminum has a very low density and high mass-specific stiffness and strength, which is why it is often used for lightweight construction [Henning, F, et al. 2011]. Besides, PA12 is the most common raw material used for AM of plastics [Drexler, et al., 2015].

Two different part geometries are used so that afterwards tensile shear test and air tightness test can be performed (see Fig. 2b). The thermoplastic specimens used for the tensile shear test have dimensions of 50 50·2 mm^3. The thermoplastic samples for tightness test are ring-like (outer/inner diameter: 44 mm / 25 mm), have a thickness of 4 mm thick and are joined with circular metal samples (diameter: 38 mm). To remove dust, grease and other contaminants from the surface, all metal samples are cleaned in an ultrasonic water bath and with acetone. The thermoplastics are solely cleaned with acetone because polyamide tends to absorb water. All specimens are fixed in overlap configuration by means of a clamping device and joined under pressure. In experiments, the joining velocity is varied, whereby the laser power (P = 500 W) and the beam diameter (d = 6 mm) are kept constant.

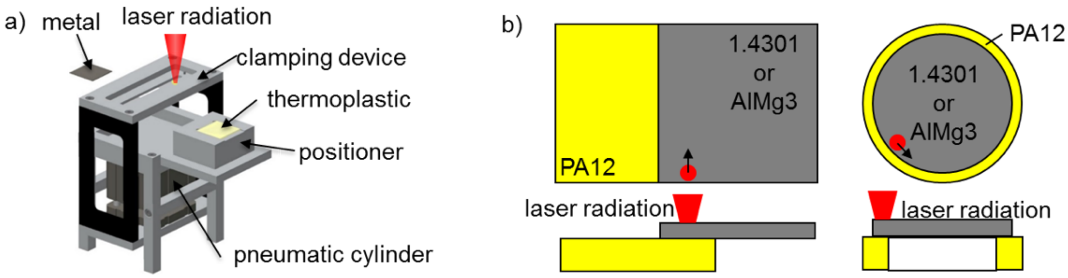

Fig. 2. (a) Schematic illustration of used experimental setup for joining, (b) Schematic illustration of used specimens

To perform tensile shear tests and analyze the breaking force F a special clamping device is used to prevent the superposition of tensile shear stress by an additional bending moment (see Fig. 3a). For the determination of the tensile shear strength of the joint, a geometrical evaluation of the wetting area must be performed. Due to the lacking transparency of the parts this can only be done after the mechanical testing. Therefore, the polyamide samples are scanned with a resolution of 300 dpi. Afterwards the wetting area can be determined with the help of appropriate software. Finally, the tensile shear stress can be calculated by the quotient of the measured wetting area and the measured breaking force.

Several methods are commonly used to determine the tightness of a material bond. In case of this paper the so-called bubble / submersion test is applied. Fig. 3b shows the testing device which is divided into two parts. The lower section, showed on top, has a cylindrical structure and a circular opening facing upwards. A cutting ring, surrounding the aperture, is used to secure the seal. At the edge of the lower section a thread and a compressed air connection are located. The upper part is a matching lid with a round opening. In advance of the testing procedure the multi-material part is placed on top of the lower part, with the metallic component heading down. It must be ensured that the test piece is situated within the rounding of the cutting ring. Afterwards the upper section is placed on top. With sufficient effort while closing the device, the cutting ring penetrates the plastic part and secures the local seal. This ensures, that only the joint is tested. Subsequently water is filled in up to the upper edge of the PA12 component. After finishing the preparations an air pressure of 2.5 bar is applied for 30 s. In case of emerging bubbles the component is not tight under the given circumstances.

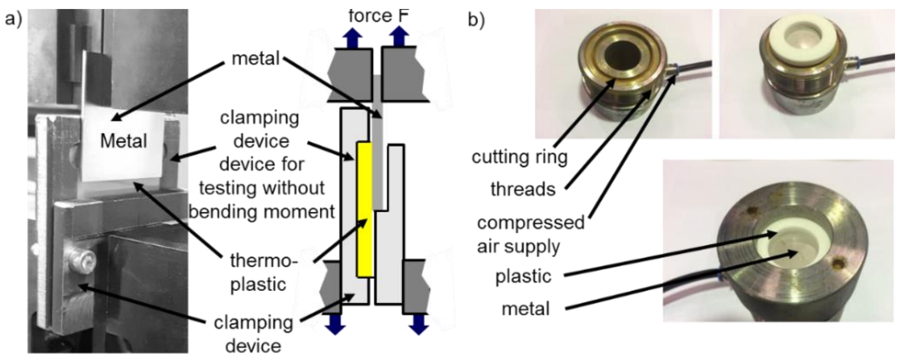

Fig. 3. Photo and illustration of performed tests: (a) tensile shear test, (b) air tightness test

3. Results and discussion

3.1. Tensile shear test

In Fig. 4 the measured wetting area and the break force as well as the calculated tensile shear strength for aluminum and stainless steel polyamide hybrids are displayed. Depending on the velocity v of the laser an approximately linear growth of the wetting area up to 379.5 ± 23.9 mm^2 can be observed. A comparable linear dependency is noticed for the breaking force F with values up to 4789.8 ± 600.6 N. Using velocities from 2 to 5 mm/s for joining aluminum polyamide hybrids, the tensile shear strengths vary between 10 and 14 MPa. The optimum of 13.5 ± 2.4 MPa is reached for a velocity of 3 mm/s. For the tested samples, adhesive fracture typically occurs. Only a few samples show mixed fractures, which means that the thermoplastics are only partly sheared off and some of it remain on the metallic surface. With velocities higher than 5 mm/s, the energy input is too low to heat the plastic up to its melting temperature, so that no stable joints can be generated.

The process window for joining hybrids consisting of stainless steel differ from hybrids consisting of aluminum. This can be explained by the fact, that less energy is needed for joining stainless steel polyamide hybrids in contrast to aluminum polyamide hybrids due to the higher absorptivity and the about ten times lower thermal conductivity of stainless steel. Joining stainless steel polyamide hybrids with a velocity of 15 to 25 mm/s resulting in wetting areas of 114.2 mm^2 to 246.0 mm^2. The lower wetting area caused by the low heat conduction losses and the comparable breaking forces results in significantly higher tensile shear strength up to 23.7 ± 1.4 MPa. Comparable high values have so far only been possible using an additional surface pre-treatment of the metal (see e.g. Engelmann et al. (2015), Amend et al. (2015), Heckert et al. (2015)).

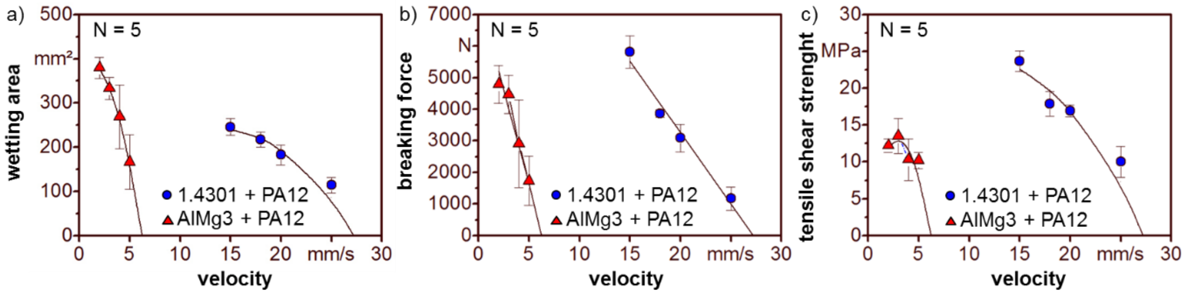

Fig. 4. Results of wetting analysis and tensile shear test: (a) wetting area, (b) breaking force, (c) tensile shear strength

3.2. Tightness test

For the tightness test the same joining parameters were used as in the above mentioned tensile shear test.

The results of the tightness test for both material combinations can be seen in Fig. 5a. Thereby, for all hybrid parts a clear tendency can be observed. Aluminum parts joined with a velocity below 3 mm/s are tight for an air pressure of 2.5 bar over 30 s. Parts with lower energy input due to higher velocities are not tight, which is illustrated in Fig. 5b. The results are consistent with the findings from the tensile shear test. Hybrid joints with a relatively high wetting area and appropriate shear strength are demonstrable tight. For aluminum, a wetting area higher than 300 mm^2 combined with at least a tensile shear strength of about 12

MPa shear strength must be given in order to achieve tight bonds. Similar results are delivered by the tightness test of the stainless steel samples. Parts with a wetting area higher than 150 mm^2 and tensile strengths higher than 15 MPa are tight. All other parameters lead to leakage.

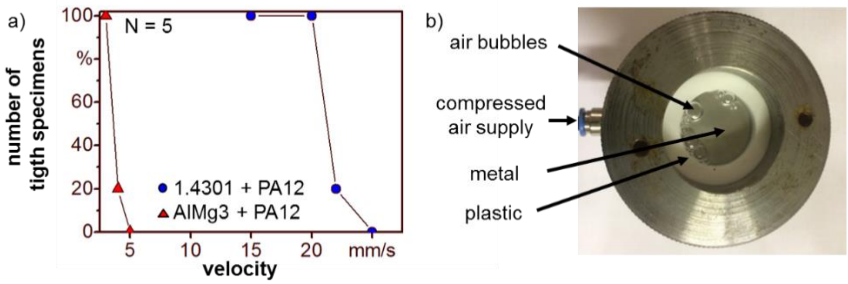

Fig. 5.(a) Number of tight hybrid specimens; (b) Top-view of tightness test for an untight hybrid specimen

4. Summary and conclusion

In the last years, thermoplastic metal hybrids are getting increasingly important as they combine the specific advantages of the individual materials optimally. Multi-material components e.g. for electronic applications require in addition to strong joints a hermetic sealing. However, suitable joining technologies for joining dissimilar materials are rare. Another emerging trend is the use of additive manufactured materials parts with the aim to create highly complex parts without the use of tools, out CAD data. All previous studies using laser-based joining of thermoplastic metal hybrids focused on injection molded or extruded thermoplastics. In this paper, the latest results on laser-based hot-melt bonding of additive manufactured plastic parts to metal sheets are presented. The experiments are performed using aluminum, stainless steel sheets as well as laser sintered polyamide parts with no pre-treatment of surfaces apart from basic cleaning. In conclusion, the reported results demonstrate that tight and partly extreme strong joint are possible. This relatively new joining technique in combination with additive manufacturing has high potential to promote the use of thermoplastic metal composites for multi-material lightweight applications in future.

Acknowledgments and Appendixes

The German Research Foundation (DFG) in the Collaborative Research Centre “CRC 814 Additive Manufacturing” has supported this research in the part project B6.

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