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Abstract

A combined keyhole and conduction laser joining process is applied to create hybrid polyamide-aluminum structures. The hygroscopic character of polyamide 6.6 is expected to lead to unstable conditions during the thermal joining process. The influence of the moisture content of the polymer base material on the quality of the joint is reviewed through optical microscopy on cross sections and X-ray microtomography on the welded assembly. It is shown that the conditioning of the polymer before laser joining has a positive effect on the process stability.

Keywords: Humidity, Hybrid structures, Laser direct joining, Lightweight design, Material moisture.

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Introduction

The reduction of structural weight is becoming increasingly important for the entire manufacturing industry. Especially the automotive engineering, aerospace engineering and transportation branches expect major improvements from new joining technologies to combine the complimentary thermal, chemical and mechanical properties of polyamide 6.6 (PA66) and aluminum by multi-material assemblies. The excellent castability and corrosion resistance of polymers combined with the conductivity and mechanical strength of aluminum enables the build of durable and efficient vehicle modules. This is why many joining techniques for materials of different classes are currently under review to access the potential for large-scale manufacturing (Amancio-Filho, 2009). However, the connection between the dissimilar materials remains the most critical aspect for containers, tanks and the encapsulation of electrical circuits that are exposed to rough environmental conditions. Not only must the assembly be able to withstand mechanical stress without damage, but it also has to deliver further functional characteristics. Distinct sealing capabilities are mandatory to prevent migration of environmentally harmful fluids and gases or ingress of contaminants, dust and water (Amanat et al., 2010a; Amanat et al., 2010b). Today, such dissimilar components are typically joined by snap joints or hemming. These principles make use of protruding sections that either lock into place in undercuts or bend around the joining partner to create a form-fitting connection. The resulting links are not able to fulfill tight sealing requirements, as the mating surfaces cannot be perfectly even. Additionally, space for gaskets and groves need to be foreseen, which in turn increases the dimensions of the joining region.

The authors have shown in previous works that laser joining offers an alternative to conventional joining techniques with outstanding properties (Lamberti et al., 2014). Laser Joining like no other thermal joining process, offers the flexibility to control the temperature curve of the joint. Taking advantage of focused laser energy can create strong joints between polyamide 6.6 and aluminum, which deliver excellent barrier properties and reduce the joint dimensions and minimize processing time. Still, the different melting points of the materials and the limited temperature stability of polymers demand a well-defined supply of thermal energy. A combination of penetration and conduction laser welding is applied to control the temperature at the interface between the joining partners while reaching high processing speed. The fast and precise heat input allows the locally controlled melting of the polymer to reduce the thermal stress introduced during the joining process. It was shown that best results are achieved at temperatures between the melting of the polymer around 255 °C and 365 °C (Lamberti et al., 2014; Schricker et al., 2016). However, this principle becomes more sensitive as the aluminum material thickness decreases. At 0.5 mm metal sheet gauge, the lifting of the weld seam and porosity inside the heated area can be observed at the process limit. These welding defects are attributed to material activities that cause the formation of gas-filled cavities inside the joining area. The appearance of gas bubbles inside the joining area was controversially discussed by other researchers, which see either pyrolysis of the polymer (Liu et al., 2014a; Jung et al., 2013a; Jung et al., 2013b; Katayama et al., 2008) or the evaporation of moisture (Amanat et al., 2010a; Kagan et al., 2005; Hopmann et al., 2014; Potente et al., 2001) inside the heat affected zone as the cause of this phenomena.

Several authors favor the appearance of bubbles because the increasing pressure is assumed to intensify the wetting of the metal surface supporting the formation of bonds (Wahba et al., 2011; Yusof et al., 2012), while others at the same time try to reduce the size and number of bubbles in order to maintain the structural strength of the base material (Kagan et al., 2005; Liu et al., 2014b; Miyashita et al., 2015; Chen et al., 2016).

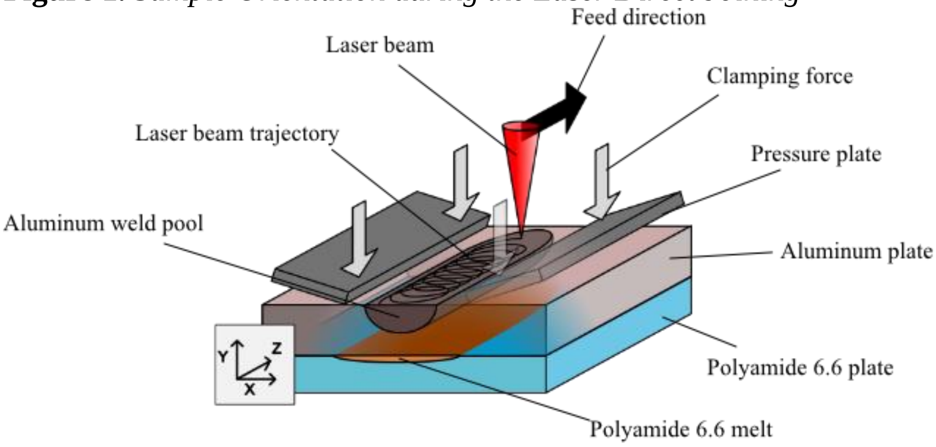
It is understood that the hygroscopic character of polyamide leads to unstable conditions during the welding operation (Schricker et al., 2016; Hopmann et al., 2014; Schricker et al., 2015). Schricker stated that the microstructure of the polyamide 6.6 and therefore also the material properties are influenced by the energy input per unit length during the thermal joining process. Hopmann connected this observation to the moisture content of the base material and pointed out the potential development of gas bubbles.

The presented experimental series was planned to better understand the impact of the polymer base material moisture on the laser assisted joining process. For the investigation, the polyamide base material moisture is varied, and the development of flaws such as voids in the joining area is captured. Additionally, two different aluminum sheet thicknesses (0.5 mm and 1.35 mm) are compared to verify the feasibility of the process for an often-demanded range and better understand the influence of the material gauge on the development of welding artifacts. Reflective light microscopy on cross sections of the joining area and X-ray microtomography on intact weld seams is applied to compare the joint quality by visual aspects. Microtomography as a Non-Destructive Technique (NDT) is an exceptional tool to resolve the fine details of the joining area and obtain volumetric information from within assembled samples.

Materials and Methods

The aluminum sheet materials used in the study were an EN AW-1050 aluminum alloy with a thickness of 0.5 mm and aluminum production material of 1.35 mm thickness, supplied by an automotive industry partner. Differences in the material composition are not expected to influence the results of the experiment.

Figure 1. *Sample Orientation during the Laser Direct Joining*



The polyamide 6.6 sheet material with a thickness of 1 mm was obtained from Goodfellow. The two different moisture conditions analyzed in this study were i) dry as molded and ii) stored under ambient conditions with the intent to cover a realistic range that represents freshly prepared material and material which has been stored for a longer period. The dried polyamide 6.6 material was preconditioned according to ISO 1110 in a vacuum chamber at 82 °C ± 2 K and a pressure of 5 mbar. The remaining moisture content of the material was below 0.2 %. The moisture content of the polyamide material stored under ambient conditions was measured to ~2%. All sheets were cut to plates of 30 mm x 20 mm. The aluminum plates were cleaned for 30 minutes in ethanol in an ultrasonic bath. The surface of the polymer plates was wiped with ethanol. All samples were blow dried with air and dried for 15 minutes in a vacuum oven before the joining experiment.

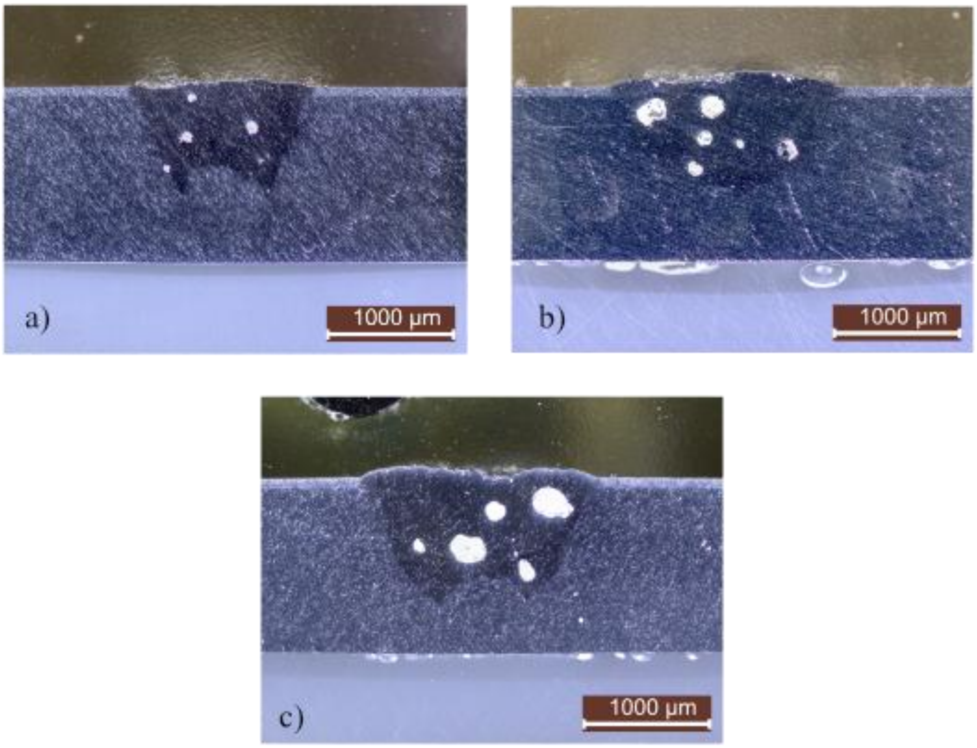
The metal and polymer plates were stacked and fixed to the machine table during the laser joining operation. A TRUMPF single mode fibre laser with an SCANLAB hurrySCAN optic was employed to provide the laser energy. The laser beam was shined onto the surface of the top aluminum layer and guided along the center line of the plates, parallel to the long edge as shown in Figure 1. Circular laser beam oscillation with an amplitude of 0.4 mm and an overlap of 75 % was applied to broaden the weld pool without a deeper penetration in the aluminum. The heat transfer to the bottom polymer plate caused the melting of the polyamide 6.6 and the wetting of the aluminum surface. A contact force of 400 N was applied on pressure plates to ensure sufficient heat conduction between the two materials. Both 0.5 mm and 1.35 mm thick aluminum plates were joined to 1 mm thick polymer plates at varying levels of laser power P [W] and beam velocity v [mm/s], expressed by the energy per unit length E = P*v-1 [J/mm]. The range in which the parameter E was varied was chosen according to the particular material thickness to provide samples without visible flaws as well as samples with clearly noticeable imperfections for both sorts of aluminum used. To visualize the effect of the material moisture on the flaws mentioned above, samples with both polymer moisture conditions, dried and stored under ambient conditions, were prepared.

The joined samples were embedded in resin and prepared for cross sections. The samples for the tomographic analysis were cut to dimensions of 20 mm x 3.5 mm. The analysis was performed on an EasyTom X-ray microtomography machine from RX solutions. The obtained resolution reached a voxel size of 4.27 µm. Reconstruction of the image data was done on the open-source platform Fiji (Schindelin et al., 2012).

Results and Discussion

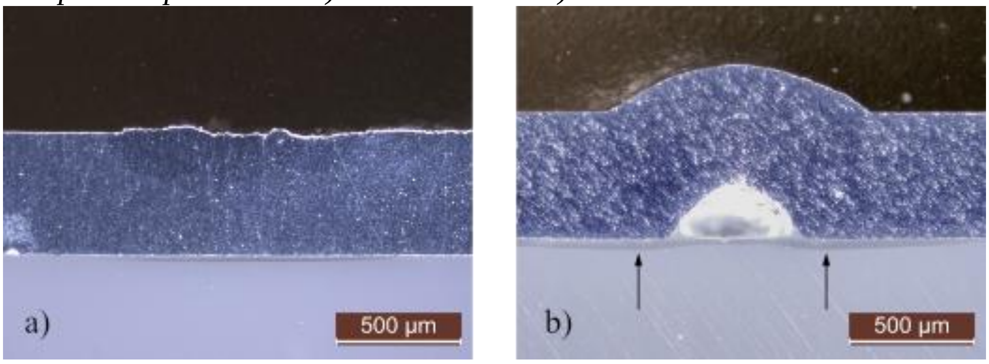
Figure 2 shows cross sections of the laser joined specimen produced with 1.35 mm aluminum and 1 mm polyamide 6.6. The aluminum weld pool can be identified in the middle of the aluminum top layer. All micrographs display gas inclusions inside the aluminum melt of the samples from the weld pool dynamics produced by the circular motion of the laser beam oscillation. It can be seen that the aluminum surface in contact with the polyamide 6.6 material remained solid throughout the joining process. Stable joints without the appearance of voids inside the polymer melt are produced at laser energy per unit length of 45 J/mm, Figure 2a. At 70 J/mm, samples show the development of voids inside the joining area, as presented in Figure 2b and 2c.

Figure 2. a) *Good Joint without Porosity in the Polymer Melt*, b) *The Formation of Voids at the Interface under High Moisture Conditions of the Polymer Base Material and* c) *The Reduced Size of Voids in Case of Dried Material*



In the case of the polyamide stored under ambient condition, the thermal joining operation creates gas pores in the range of a tenth of a millimeter inside the polymer melt. These flaws can extend across a wide area of the melting region in the polyamide. Figure 2c reveals that drying the polyamide before the laser joining leads to a notable reduction of the gas pores size. Furthermore, after the drying procedure, the appearance of these gas inclusions is restricted to the interface region at the center where the highest temperatures occur.

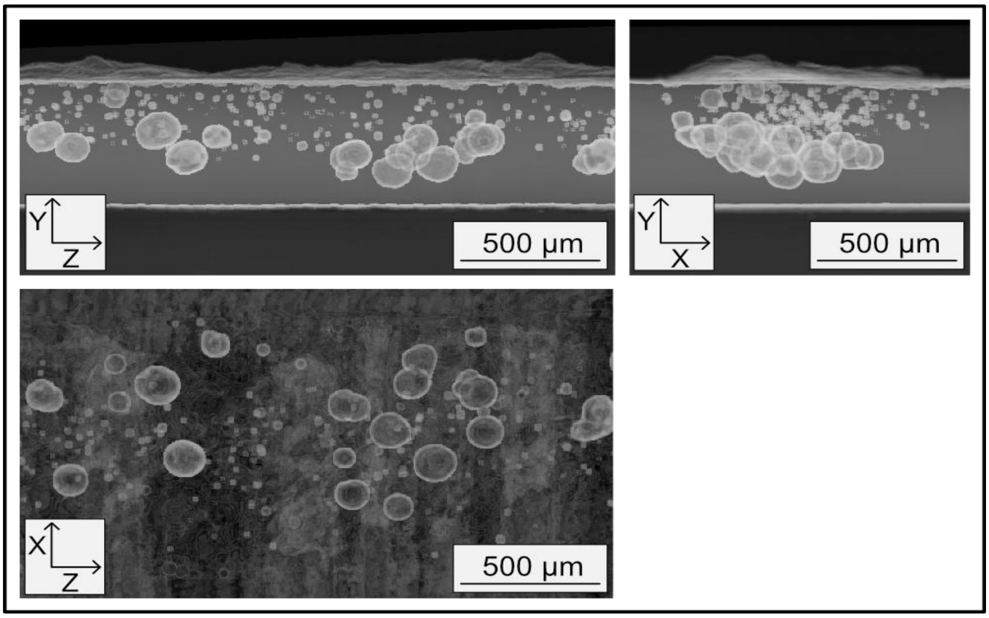
Figure 3. *Cross Section Micrographs of Laser Joined PA66-aluminium Samples Prepared with a) 3.15 J/mm and b) 3.6 J/mm*



Reducing the aluminum top layer's thickness to 0.5 mm requires adapting the supplied laser energy during the joining operation. Figure 3a demonstrates similar results to figure 2a after laser joining of 0.5 mm aluminum with 1mm polyamide at 3.15 J/mm energy per unit length. Thus, good joints without visible material damage in the joining region can be produced with both 0.5 mm and 1.35 mm aluminum sheet thicknesses. The combination of 0.5 mm aluminum and moist polyamide at higher energy per unit length (3.6 J/mm) stimulates the formation of gas pores on the metal side of the joint as shown in Figure 3b. The application of the joining force via the pressure plates to the left and right of the welding line compresses the melted zone tightly. At the same time, the softening of the aluminum in the heat affected zone facilitates the concentration of the released vapor in the center of the joining region. The micrograph in Figure 3a shows that the gas pressure lifts the weld seam over the polymers heat affected zone. The greater depth of the melting pool in the polymer, at the position of the arrows to the left and right of the gas capillary in Figure 3b, is evidence that the melting of the polymer continues, after the separation of the materials in the center has happened. No bubbles are located inside the polymer melt. This observation is in contrast to the examples shown in Figure 2, where the gas pores are restricted to the polymer melt phase. Figure 3b does not show signs of polymer combustion, which would indicate direct laser irradiation onto the underlying PA66.

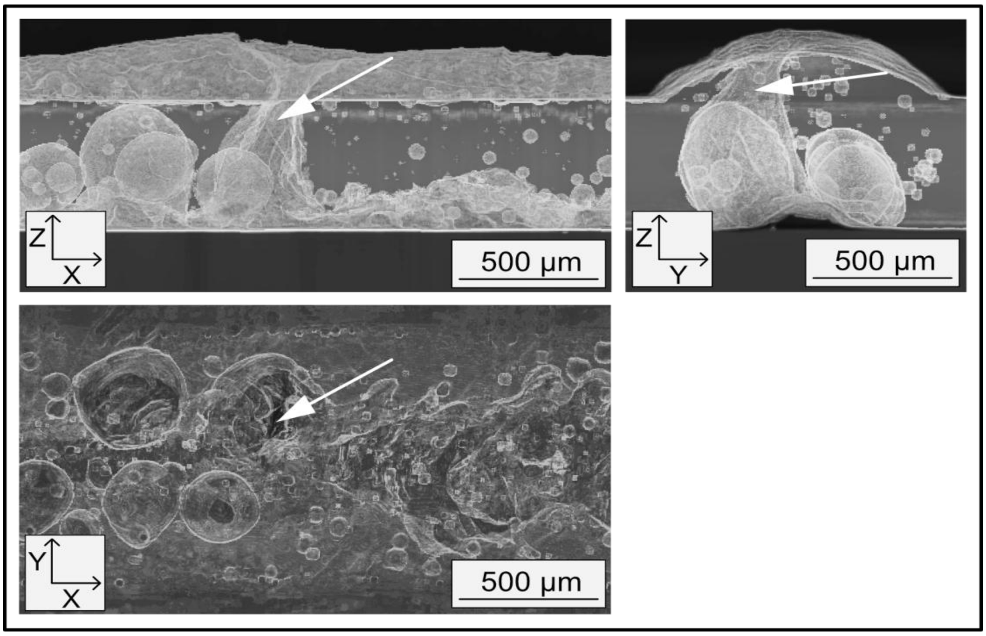
The volumetric information of the assembly obtained by X-ray microtomography is presented in the Figures 4 and 5. All tomographic projections are oriented according to the coordinate system shown in Figure 1. The top left position (Y-Z plane) illustrates the projection from the side of the welding line with the 0.5 mm aluminum sheet on top and the welding direction from left to right. The top right image shows the view in welding direction (Y-X plane) and the view from the top can be seen at the bottom left (X-Z plane).

Figure 4. *X-ray Tomographic Reconstruction of the Joining Area of 0.5 mm Aluminum and Dried PA66 Laser Joined at 3.6 J/mm*



The tomographic images of the samples that have been dried before the thermal joining do not confirm gas pores inside the joining area (Figure 4). It can be seen that the development of voids is restricted to the aluminum melt pool, mainly at the root. The porosity does not coalesce and the voids do not connect to the polymer-metal interface.

Figure 5. *X-ray Tomographic Reconstruction of the Joining Area of 0.5 mm Aluminum and PA66 Stored under Ambient Conditions and Laser Joined at 3.6 J/mm*



Strong porosity in the aluminum is evident for the combination of polyamide with high moisture content and 0.5 mm aluminum material sheets shown in Figure 5. The volumetric analysis of these samples demonstrates that the metal and polymer have been completely separated below the aluminum melt pool. The reduced stiffness in the aluminum heat affected zone and the built of gas pressure at the interface leads to the formation of a hollow channel all along the weld line. The tomographic projection discloses a potential risk that pores inside the aluminum melt break through and connect the channel from the polymer-metal interface to the top surface of the aluminum, indicated by the arrows in Figure 5. In this example, the joint with PA66 in moist condition cannot provide the demanded tight sealing capabilities. The tomography confirms no direct laser irradiation on the polyamide 6.6 material.

Conclusions

The experimental series has shown that the material moisture content of polyamide 6.6 has the ability to influence the process stability during the laser joining to aluminum and the development of gas pores in the joining area. The humidity captured inside the polymer material evaporates during the laser joining process. The gas increases the pressure in the melt, and eventually, gas cavities are formed. X-ray microtomography and micrographs of cross sections demonstrate that the pressure at the interface can lead to the formation of a hollow gas channel along the weld line that potentially breaks through the aluminum weld pool and destroys the tight sealing capabilities of the joint. This study proves that reducing the moisture content of the polymer base material extends the stability of the laser joining process and reduces the formation of gas pores inside the melting region of the polyamide 6.6. It was shown that under optimum conditions a joint without gas cavities could be created with aluminum sheets as thin as 0.5 mm.

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