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Joining aluminium and poly(lactic acid) specimens by laser beam – a feasibility study

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Abstract. In this article, our main aim is to demonstrate and prove that it is feasible to join aluminium and poly(lactic acid) (PLA) specimens by laser beam. We investigated the effects of structuring the surface of the aluminium specimens with corundum blasting and joining speed and used three types of PLA (with the same D-lactide content but different average molecular weights) to investigate the effect of the viscosity of the polymer melt on the load-bearing capacity of the joints. Joined aluminium-PLA specimens were successfully manufactured and examined with standard lap-shear tests. We found that both surface structuring, joining speed and the type of PLA material influenced the load-bearing capacity of the aluminium-PLA joint.

1. Introduction

An important aim of industrial research and development is to integrate numerous structural elements into one complex part. Costs can be decreased with the use of automatable technologies and low-density materials like aluminium, polymers and polymer composites. In the vehicle industry, this results in less weight, and thus less fuel consumption and less harmful gases emitted during the lifetime of the vehicle [1-3]. Another trend in the vehicle industry is to use fewer types of materials to increase the effectiveness of recycling. The 2000/53/EC directive requires that at least 85 wt% of the material in a scrap vehicle must be reused or recycled [4]. Thus, in the last decade, much research has been focused on the development of materials that are easy and cheap to manufacture and recycle. One such polymer material is poly(lactic acid) (PLA), which is biodegradable and can be synthesised from renewable resources. It is widely researched, as it is a promising material in certain applications (such as containers and food packaging). Its mechanical properties, however, do not yet permit its use in products with a long lifetime [5-7].

The R&D of direct joining techniques of polymers and metals (without the use of any additional materials or technological steps) has been a hot topic in recent years [8, 9]. There is a special focus on researching the applicability of easily automatable, quick polymer welding techniques (such as techniques based on friction, and ultrasonic and laser welding). In all of these, the polymer material is heated, melted and pushed into the surface structures of the metal, promoting the formation of strong, shape-connected joints [10, 11].

As metals and polymers have different chemical structures and melting temperatures, only adhesive joints can be created between them with welding techniques. Besides chemical connections creating the



necessary adhesion, the surface structure of the metal can also significantly influence the strength of the joint. But, as numerous publications prove, it is possible to manufacture strong joints between metal and polymer materials with joining technologies such as friction stir welding, ultrasonic welding and laser welding. In these, mostly steel and aluminium, engineering thermoplastics and thermoplastic composites (e.g., unreinforced and glass fibre-reinforced polyamide (PA, PA-GF), polycarbonate (PC), and polyethylene terephthalate (PET)) were used and examined [12-14]. However, the joinability of aluminium and PLA has never been investigated before.

In this feasibility study, we are going to prove that strong joints between aluminium and PLA can be manufactured. We chose an aluminium alloy that is widely used, even in the vehicle industry, and used grit blasting to create structures on its surface. We also used three different PLA materials and three different joining speeds to examine the effect of multiple parameters on the load-bearing capacity of the aluminium-PLA joints.

2. Materials and Methods

2.1. Materials

In our experiments, we used 116 mm × 46 mm × 1.4 mm (length × width × thickness) AA1050A-type aluminium specimens. The chemical composition of the aluminium (Table 1) was confirmed by optical emission spectrometry (OES) and energy-dispersive spectroscopy (SEM-EDS). The aluminium specimens were grit blasted with corundum of two different sizes (80-100 μm and 300-400 μm). The surface roughness of the aluminium specimens (in factory-rolled “as-received”, and corundum-blasted states) was measured with a surface roughness measuring device (Mitutoyo SJ-400) and by scanning electron microscopy (SEM).

Table 1. Chemical composition of the AA1050A-type aluminium alloy

	Chemical composition (wt%)							
	Al	Mg	Si	Cu	Mn	Ti	Fe	Other
AA1050A	99.50	0.15	0.12	0.04	0.03	0.01	0.01	0.14

Three types of PLA (Ingeo Bioplastics 2500HP, 3100HP and 3260HP) with different average molecular weights were used (Table 2). The PLA granules were dried in a drying oven at 80°C for 6 hours. After drying, flat, square-shaped specimens (80 mm × 80 mm × 2 mm in size) were injection moulded on an Arburg AllRounder Advance 270S 400-170 injection moulding machine (an ascending temperature profile with 5 °C increments was used, the temperature at the screw tip was set to 200 °C). From these, 80 mm × 25 mm × 2 mm rectangular specimens were cut with the use of a VersaLaser VLS 2.30 type CO₂ laser cutter. The average transparency of the PLA specimens was measured with a Perkin-Elmer Lambda 1050 spectrophotometer (Table 2).

Table 2. Average molecular weight and MFI values of PLA materials
(* MFI values are taken from the Technical Data Sheets of the materials)

PLA material	Weight-average molecular weight (kDa)	Melt Flow Index* (MFI, 210 °C, 2.16 kg) (g·10min ⁻¹)	Average total transparency at 950 nm (%)
Ingeo 2500HP	175	8	90
Ingeo 3100HP	138	24	89
Ingeo 3260HP	105	65	90

2.2. Joining process and measurement method

To join the aluminium and PLA specimens, we used a Trumpf TruDiode 151-type laser welding machine (wavelength was 950 nm) at 150 W power output. Both the aluminium and polymer specimens were cleaned in an ultrasonic bath for 5 minutes in methanol before the joining process. The specimens were joined in an overlapped configuration: the polymer was placed on top of the aluminium, and then both materials were irradiated by the laser beam (transmission joining; Figure 1). During this process, the

laser beam passed through the PLA specimens, and its energy was absorbed in the aluminium, producing heat. It is crucial that the transparency of the polymer specimens is high enough to let most of the laser beam pass through them with the least amount of deflection and reflection possible. Some of this heat was then conducted to the PLA specimens, which were melted as a result. The melted PLA then wetted the surface of the aluminium specimens, filled in the surface structures and after cooling down, shape-connected joints were formed.

The specimens were clamped together during the joining process with a weight plate ($m=1.25$ kg). In this plate, a window with an appropriate size was cut, so the laser beam could irradiate the materials below the plate. The length of the path that the laser beam irradiated was set to 169 mm, the laser beam started from the spot marked with an X, and its path is shown as a red, dashed line in Figure 1.

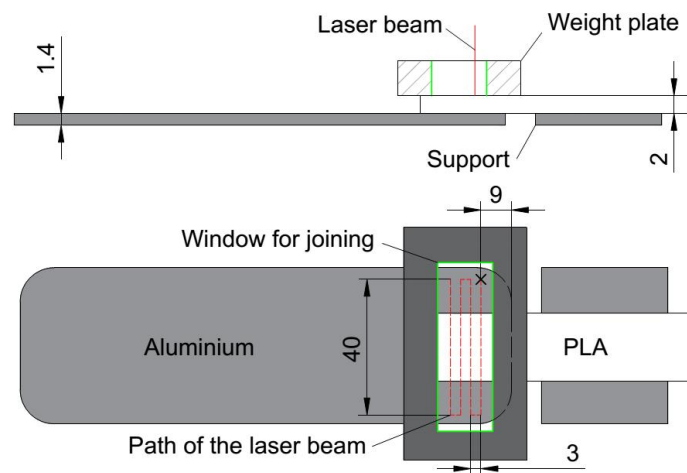


Figure 1. Overlapped configuration of specimens for joining and the path of the laser beam in the joining process (all numerical values in this figure are in mm)

The variable parameter of the joining process was joining speed, which was set to 1, 2 and 3 $\text{mm}\cdot\text{s}^{-1}$, as at these speeds, lasting joints were formed with all three PLA materials. Slower joining speeds meant that the laser beam irradiated the specimens longer, thus more heat was formed, and the PLA specimens melted more. At higher joining speeds, the strength of the joints became inconsistent: in some cases, joints did not even form, while in other instances, joints failed after the joining process finished.

We used a Zwick Z005 universal testing machine to measure the load-bearing capacity of the joined specimens under shear load, at room temperature. Measurement speed was set to 5 $\text{mm}\cdot\text{min}^{-1}$.

3. Results and discussion

3.1. The surface roughness of aluminium

Firstly, we tried to join the PLA specimens with aluminium specimens without any surface structuring (in “as-received” state). We found that no joint can be manufactured at any of the joining speeds because the PLA did not properly wet the surface of the aluminium specimens. Our literature review revealed that certain surface preparation techniques, such as grit blasting, can solve this problem by forming structures on the surface of the aluminium. This increases the size of the area where shape-connected joints can form and thus, the load-bearing capacity of the joints increases. We used corundum of two different sizes (the average diameter of the corundum was 80–100 μm and 300–400 μm) to structure the surface of the aluminium specimens before joining. Average surface roughness (R_a) and average roughness height (R_z) values were measured (Table 3).

Table 3. Average surface roughness (Ra) and average roughness height (Rz) for corundum-blasted aluminium specimens

Average corundum size	Ra (μm)	Rz (μm)
“As-received” surface	0.47	3.15
80-100 μm (“Smooth”)	1.89	15.73
300-400 μm (“Rough”)	6.00	41.97

By grit blasting with the two different types of corundum, we were able to increase the average roughness of the surface by a factor of 4 (“smooth”) and 12 (“rough”). Figure 2 shows SEM images of the surfaces of the “as-received” and the corundum-blasted specimens. The “as-received” surface (Figure 2a) shows the imprint (parallel lines) of the rolling device used in manufacturing the aluminium sheet. These lines were parallel on the whole surface of the specimens, and thus, there was little chance for shape-connected joints to form between the aluminium and the PLA specimens. Figures 2b and 2c show the corundum-blasted surfaces of aluminium specimens. During the grit blasting process, surface structures (ridges and trenches) formed. The polymer melted during the joining process was able to flow into these structures. This made it possible for shape-connected joints to form, which also influenced the global strength of the aluminium-PLA joints.

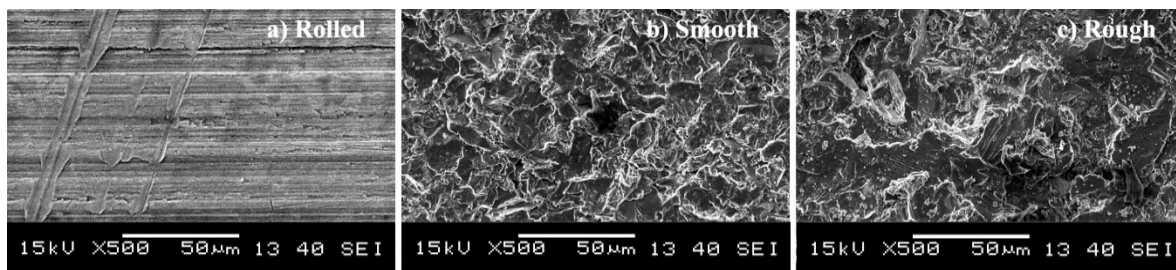


Figure 2. SEM images of aluminium specimen surfaces, a) “as-received” (factory rolled), b) “Smooth” (after surface prep. with 80-100 μm corundum), c) “Rough” (after surface prep. with 300-400 μm corundum)

3.2. Shear tests

During the shear tests, the clamping jaws were offset so that no additional torque (caused by the clamping) loaded the specimens. Results show that strong joints can be manufactured. The shear load-bearing capacity (Figure 3) of the aluminium-PLA joints reached about 66% of the average tensile load-bearing capacity of the 3260HP PLA material. This is the result of tensile tests on three 80 mm \times 25 mm \times 2 mm specimens. The tensile tester was the same Zwick Z005 testing machine and testing speed was 5 mm \cdot s⁻¹.

Both the type of the PLA material and joining speed influenced the quality and load-bearing capacity of the joints (Figure 3). The optimal parameter combination for maximum load-bearing capacity of the aluminium-PLA joint seems to be the “smooth” corundum-blasted aluminium, 2 mm \cdot s⁻¹ joining speed and 2500HP PLA. At a joining speed of 1 mm \cdot s⁻¹, the reduction in load-bearing capacity of the joints was most probably caused by the degradation of the PLA because of the high heat input. High heat promotes the thermal degradation of the material through random chain scission, cis-elimination and trans-esterification reactions. As the PLA specimens were not dried before the joining process took place, water molecules were also present inside the material, which further increased the molecular degradation of PLA through hydrolysis, as discussed in [15, 16]. At 3 mm \cdot s⁻¹, the heat input was too low (because joining speed was too high), which again caused the load-bearing capacity of the joints to decrease.

In almost all of the specimens manufactured with 1 and 2 mm \cdot s⁻¹, the PLA specimen failed cohesively, at the edge of the aluminium specimen. This was caused by the high temperature gradient in and the low thermal conductivity of the PLA, which probably promoted the degradation of the

material. The failure mode of the joints made with a joining speed of $3 \text{ mm}\cdot\text{s}^{-1}$ varied between adhesive peeling of the PLA from the surface of the aluminium and cohesive failure of the PLA.

At $1 \text{ mm}\cdot\text{s}^{-1}$, the melt viscosity of the PLA did not influence the load-bearing capacity of the joints. This was probably because the effect of shape-connected joints on load-bearing capacity was compensated by the degradation of the PLA material. Our theory was that if we used a PLA with a high melt viscosity, the polymer melt could more easily fill the surface structures of the aluminium specimen, and thus, a stronger joint could be manufactured. This theory, however, was contradicted by joints manufactured at $2 \text{ mm}\cdot\text{s}^{-1}$. In these tests, the joints with the highest load-bearing capacity were manufactured with the PLA with the lowest melt viscosity. We will further examine this phenomenon and its causes in the future. At a joining speed of $3 \text{ mm}\cdot\text{s}^{-1}$, it seems that the melt viscosity of the PLA did not have a significant effect on the load-bearing capacity of the joints.

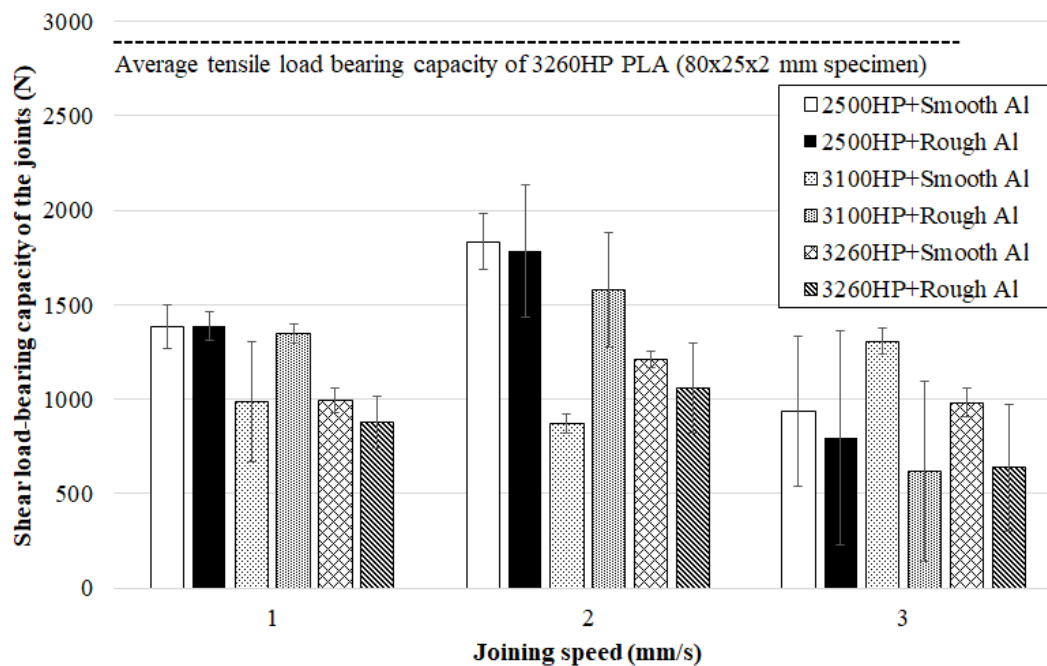


Figure 3. The shear load-bearing capacity of the aluminium-PLA joints

In almost all the cases, the joints manufactured with the “Smooth” aluminium specimens had an equal or better load-bearing capacity compared to the joints manufactured with the “Rough” aluminium surface. This was probably because in the case of “Smooth” aluminium specimens, the surface ridges and trenches were shallower, but more structures were formed on the surface compared to the “Rough” aluminium specimens. The polymer melt can easily fill shallow surface structures, forming many shape-connected joints. At the bottom of deep surface trenches, however, air bubbles can remain under the polymer, decreasing the global strength of the joint (as reported in [17]).

In some cases, near the hole in the weight plate that we used to clamp the materials together, the PLA material was partly or fully displaced (the PLA material formed an arch, marked with a red curve in Figure 4), in the region where the materials were not pressed together. This led to high standard deviations of the measurement results, as the specimens and the area where the PLA properly wetted the aluminium differed from specimen to specimen, even when the process control parameters were the same.

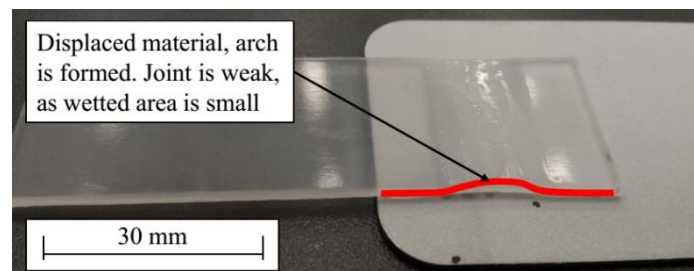


Figure 4. Arching of the 3260HP PLA specimen when the joining speed was set to $3 \text{ mm}\cdot\text{s}^{-1}$

4. Conclusions and future plans

We showed that it is possible to join aluminium and PLA specimens by laser beam and that the joints can be strong if the surface of the aluminium specimens is properly structured. In our experiments, we used corundum blasting to change the surface structure, and three different types of PLA materials (these had different average molecular weight, but the same D-lactide content). Our results showed that the most durable joints were manufactured with the use of corundum-blasted aluminium and the PLA with the highest average molecular weight, at a joining speed of $2 \text{ mm}\cdot\text{s}^{-1}$. In the future, the clamping system must be improved, and further tests are necessary to evaluate the load-bearing capacity of the joints.

We are currently working on a clamping system, in which the specimens can be clamped together between a highly transparent glass plate and a plate with low thermal conductivity. With this clamping system, we will be able to prevent the arching (displacement) of the polymer material. We are also going to investigate other polymer materials used in the vehicle industry (for example, polyamide and polypropylene and composites based on these materials) and other surface structuring techniques (for example laser ablation of the aluminium specimens).

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