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FULL RESEARCH ARTICLE

Joining technology of additively manufactured components: effects on the bonding strength for the adhesive application through inner channels

Michael Ascher[1] · Stefan Brenner[1] · Genny A. Pang[1] · Ralf Späth[1]

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Abstract
The maximum size of additively manufactured (AM) components is restricted due to the confined building space of the manufacturing machines. Component separation and subsequent joining can be an effective way of manufacturing larger components using AM processes. For joining of AM components, adhesive bonding provides great potential for not constraining the adherend's geometry, as long as the adhesive can still be applied to the adhesive surfaces of the adherends. This work investigates the effectiveness and applicability of additively manufactured inner channels to improve the adhesive application. A circular adhesive single lap joint between a laser-based powder bed fusion (PBF-LB) component made of AlSi10Mg and a cold drawn aluminum round bar was considered. The PBF-LB components were designed with varying geometric complexity to implement different adhesive application concepts. Subsequently, the bonded joints were subjected to static tensile tests. The fracture strength of joints where the adhesive was applied by injection into AM inner channels exceeds the fracture strength of joints where the adhesive was injected into geometries manufacturable by subtractive machining, and also exceeds the fracture strength of joints where the adhesive was pre-applied.

Keywords Additive manufacturing · Powder bed fusion · Adhesive bonding · Inner channel · Depowdering

1 Introduction

Additive manufacturing (AM) processes like the laser-based powder bed fusion (PBF-LB) process offer a great freedom in design. This can be exploited by adding more functions to a single component or by realizing complex lightweight designs. As geometrical complexity increases so do the manufacturing costs. This is due to the need for additional support structures, rework, and extended manufacturing time. Another boundary condition is given by the confined building space of the manufacturing machines, which limits the achievable component dimensions and, therefore, the usability of AM processes for various applications. Component separation and subsequent joining can be an effective way of repealing size limitations and decreasing manufacturing cost. Adhesive bonding provides great potential with low additional weight and not imposing restrictions on the adhesive surface´s geometry or the adherend´s material.

In terms of adhesive bonding, the adhesive application presents a major technical challenge with respect to bonding strength and process reliability [1]. Traditional pre-application of adhesive to the adhesive surfaces promotes application errors due to numerous individual working steps which are usually carried out manually. When implementing the application by injection, the number of manual working steps can be reduced to the expense of additional manufacturing effort and resources. When it comes to adhesive bonding of AM components, one of the most outstanding design features of AM processes can be utilized to overcome these drawbacks. Complex inner channel geometries can be used to transport and apply the adhesive to the adhesive fill gap prescribed by the aligned adherends after the adhesive was injected into a designated inlet in the AM component.

The scientific issue addressed in this paper is to investigate to which extend the freedom of design underlying the PBF-LB process can be utilized to improve the adhesive

✉ Michael Ascher
michael.ascher@unibw.de

1 Faculty of Mechanical Engineering, Institute for Design and Production Engineering, University of the Bundeswehr Munich, Werner-Heisenberg-Weg 39, 85577 Neubiberg, Germany

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application with respect to bonding strength, process reliability, and handling expense.

This article is organized in five sections. Following this introduction (Sect. 1), a literature review provides information about Design for Additive Manufacturing (DfAM) recommendations regarding the manufacturability of inner channels by the PBF-LB process and general requirements for the adhesive application in structural bonding (Sect. 2). In Sect. 3, the manufacturing process of adhesively bonded test joints between PBF-LB components and an aluminum round bar is presented. The PBF-LB components feature different designs for implementation of associated adhesive application concepts. Subsequently the test joints were subjected to static tensile tests. As part of Sect. 4, the results of the static tensile tests are evaluated and discussed. The last section concludes this study by summarizing the most useful findings.

2 State of the art

2.1 Laser-based powder bed fusion (PBF-LB)

Powder bed fusion (PBF) is defined as an additive manufacturing process in which thermal energy selectively melts areas of powdered material layer-by-layer [2]. The powder for each layer is supplied by a feeding system and distributed by a spreading device on a build platform. In case of the laser-based (LB) process, the thermal energy is introduced by a laser beam guided by a deflection mirror. The contours specified by the deflection mirror are melted locally and solidify to form a solid layer of material. Subsequently, the build platform is lowered by the desired layer height and the procedure repeats. Thermoplastic polymers, ceramics, pure metals and metal alloys in powder form serve as starting products. If metallic powder is involved, support structures are required to support overhangs and reduce thermal distortion. After completion of a build job, loose powder residues and the remaining support structures need to be removed.

As there are no manufacturing constraints concerning tool accessibility or undercuts [3], the PBF-LB process enables the realization of sophisticated free-form geometries (for example biomedical structures [4]), lattice structures [5] or complex inner channels. The latter is often used to implement conformal cooling channels in applications like injection-molding tools [6] or gas turbines [7] to increase their efficiency. The accessibility of inner channels for the mechanical removal of support structures or powder residues is severely limited. For this reason, the overhanging surfaces of channels need to be manufactured unsupported, and the design must consider the de-powderability. General DfAM recommendations for the maximum channel diameter manufacturable unsupported from the aluminum alloy AlSi10Mg using the PBF-LB process range from 6 to 9 mm [3, 6, 8].

Whenever overhangs are built free of support, sag and dross effects occur [9]. These effects constrain the minimum channel diameter due to complete fusion or sintering of the intended cavity. In [10], a relationship between the channel length and the minimum diameter manufacturable with the aluminum alloy AlSi10Mg was found. For channel lengths below 20 mm the minimum diameter is given to 0.75 mm and for channel lengths between 20 and 40 mm the minimum diameter is specified to 1.0 mm. To diminish implications resulting from dross formation or sagging, a droplet-like shape can be used for the cross section of the inner channel [8, 10, 11].

2.2 Adhesive application in structural bonding

The adhesive application technology has a decisive influence on the strength and reliability of the bond. It must therefore be ensured that the adhesive application is carried out correctly and reliably. This means that no application errors such as mixing errors, over-/underdosing or uneven distribution occur. The application process can be divided into dosing, mixing and distribution of the adhesive [1]. The traditional approach towards adhesive application includes successive manual mixing of the adhesive, volumetric dosing, and areal distribution using a scraper. In case of circular adhesive joints, the adherends should be merged with a rotating motion in order to prevent the adhesive from being pushed out of the adhesive fill gap [12]. These manufacturing steps can be combined to form a single step if they are implemented by injection [13] and applicable geometrical features for the adhesive distribution are provided. In this case, the adhesive is dosed pressure / time controlled or with optical monitoring, and mixing is accomplished with a mixing nozzle that applies the adhesive punctiform, distributing the adhesive contactless within the adhesive fill gap prescribed by the aligned adherends. As part of this approach, the components are merged prior to the adhesive application process and therefore the risk of underdosing or irregular distribution can be minimized.

In [14], a case study demonstrates that it is not possible to completely enrich the adhesive fill gap of a circular SLJ featuring an overlap length of $l_o = 30$ mm, a nominal diameter of $d_n = 30$ mm and a nominal adhesive fill gap height of $h = 0.1$ mm by injecting the adhesive (*3 M Scotch-Weld DP490*) into a single through hole in the AM component using a manually operated cartridge squeezing device. Instead, it is necessary to introduce the adhesive at multiple locations to the adhesive fill gap. This can be accomplished by setting up more through holes in the AM component or by distributing the adhesive using inner channels [15]. Methods to align the adherends while injecting the adhesive must be utilized in order to ensure a uniform adhesive fill gap [14].

3 Materials and methods

3.1 Test joints

The case for the following investigations is given by an exemplary circular SLJ featuring an overlap length of l_o = 30 mm, and a nominal adhesive fill gap height of h = 0.1 mm. The adherends to be adhesively bonded are a PBF-LB component made of AlSi10Mg (= outer adherend; nominal inner diameter d_i = 30.2 mm) and a semifinished cold drawn aluminum 6061 round bar (= inner adherend; nominal outer diameter d_a = 30.0 mm). The PBF-LB component is concentrically aligned to the aluminum round bar by a centering surface (nominal inner diameter d_i = 30.0 mm) and connected to a steel clamping element using a special fitting bolt (Fig. 1). The 2-component adhesive DP490 (*3 M Scotch-Weld*) used for bonding of the adherends is a pseudoplastic construction adhesive based on epoxy resin.

For implementation of different adhesive application concepts, the PBF-LB components are comprised of different geometrical features. PBF-LB components containing inner channels used for adhesive application by injection (IAM) are compared to PBF-LB components where the application was accomplished by injection into simpler geometries manufacturable by subtractive machining (ISM) [14] and also compared with PBF-LB components where the adhesive was pre-applied to the adhesive surface before merging the adherends (PA). The different designs of outer adherends are depicted in Fig. 2.

The positioning of the ten outlets implemented in the IAM-components ensures complete coverage of the adhesive surface with adhesive [16]. To compensate for the loss in perfused cross-sectional area due to sag and dross effects, the cross-sectional conversion of the inner channels was

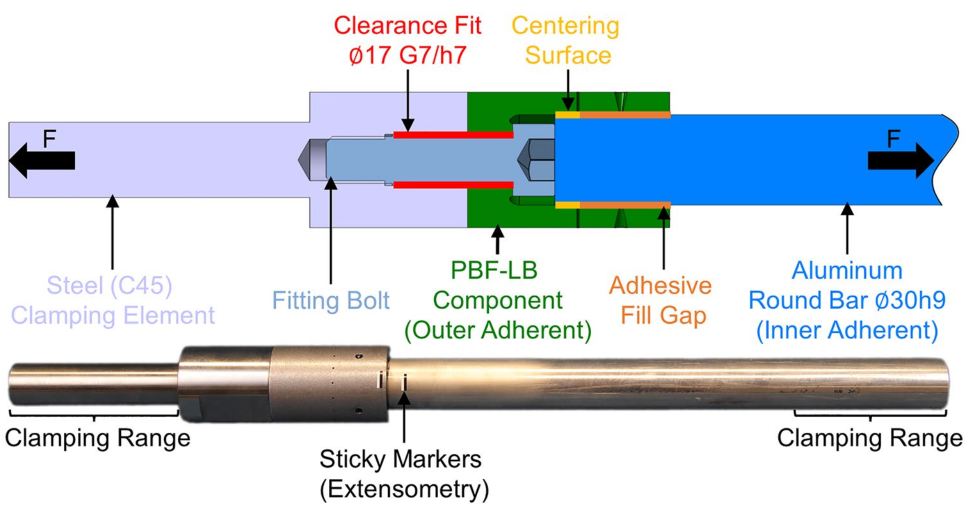
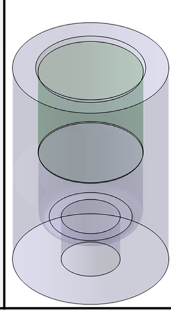
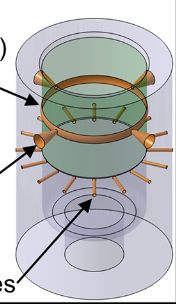
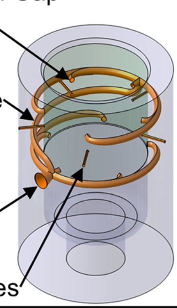


Fig. 1 Schematic representation and implementation of a test joint for static tensile tests

Fig. 2 Geometry of PBF-LB components for implementation of different adhesive application concepts

Application Concept	**P**re-**A**pplication	Application by **I**njection - **S**ubtractive **M**achining [14]	Application by **I**njection - **A**dditive **M**anufacturing
Indication	PA	ISM	IAM
Geometrical Features • Adhesive Surface • Injection/ Distribution Geometries		Groove for Adhesive Distribution (2.5x0.4 mm) 4 Injection Points + 4 Outlets to Adhesive Fill Gap Venting Holes 	10 Outlets to Adhesive Fill Gap Inner Channels for Adhesive Distribution (Ø2 mm) 1 Injection Point Venting Holes 

manufactured with a 45°-droplet-like shape (tip oriented in the build direction) and the minimum nominal diameter of 2 mm was met [16]. The positioning of the venting holes is based on the computational fluid dynamics analysis of a multiphase model introduced in [16], which revealed the most critical spots for air inclusions.

The ISM-components feature four conical through holes for the injection of adhesive and a semi-circular groove (width 2.5 mm, depth 0.4 mm) for the adhesive distribution. The groove is introduced directly to the adhesive surface. [14]

The PA-components do not contain geometrical features that allow the adhesive to be injected. The adhesive must be applied manually using a scraper before merging the adherends.

Twelve PBF-LB components (four components for each application concept) were produced in-house using an *SLM®125* PBF-LB machine. Due to build plates basic dimensions of 125 × 125 mm it was possible to manufacture four components as part of single build job. The associated manufacturing parameters can be taken from Table 1.

Commercially available AlSi10Mg powder from the manufacturer SLM Solutions with a particle size between 20 µm and 63 µm was used throughout. To suppress influences on the surface roughness based on component orientation [17], the PBF-LB components were printed with the axis of rotational symmetry aligned parallel to the build direction.

To establish the real adhesive fill gap height, the PBF-LB components´ geometry was measured using a 3D-Scanner (*Keyence VL-500*). The minimum inner diameter of the adhesive surface was evaluated to 30.170 mm and the maximum inner diameter was evaluated to 30.176 mm. Considering the manufacturer's tolerance specifications for the outer diameter of the aluminum round bar of $\varnothing 30h9$, the actual adhesive fill gap height ranges from 0.085 mm to 0.114 mm.

Regarding the de-powdering procedure of IAM-components, the three methodological steps described below were applied repeatedly to four components still attached to the build plate. Powder residues on the outside of the components were removed before the build plate was taken from the machine. The amount of powder removed from the inner channels by each repetition of a step was quantified using a weighing procedure. The entirety of components plus build plate was placed on an electronic precision scale (*Sartorius U 4600 P*) after every repetition of a step and the difference in weight with respect to the last measurement was taken as the residual powder removed. When there was no more change in residual powder weight quantifiable the next step was taken and the de-powdering procedure was assumed to be successful when it was not possible to remove more residual powder from the components. As part of the step one, the nozzle of a wet separator was placed on top of every component for three seconds with the bottom sealed by the build plate. For step two, the build plate was placed in an ultrasonic bath for 5 min. The components were not soaked to exclude the risk of toughening the residual powder inside the inner channels. Step three includes soaking of the components and subsequent blowing out with compressed air at a pressure of six bar.

After separating the de-powdered components from the build plate and facing the bottom surface the succeeding steps towards the final test joint (Fig. 1) are as follows:

1. Pre-treatment of the adherends´ adhesive surface in consideration of [18]

i Mechanical pre-treatment

- Aluminum round bar: 3D sanding fleece (3 M Scotch-Brite A-VFN)
- PBF-LB component: 1 h vibratory finishing (Müller Mechanik MMTV-5321)

ii Rinsing with isopropyl
iii Cleaning in ultrasonic bath with distilled water
iv Drying
v Fastening of PBF-LB component to clamping element using a fitting bolt

2. Bonding process (Process A. or B. or C.)

A. Pre-application (PA)
i. Adhesive application to adhesive surfaces of both adherends using a scraper
ii. Merging of PBF-LB component and aluminum round bar with a rotating motion
iii. Concentric alignment through centering surface
B. Application by Injection: Subtractive Machining (ISM)
i Merging of PBF-LB component and aluminum round bar and concentric alignment through centering surface
ii One by one crosswise injection of adhesive at four injection points

Table 1 Machine parameters used for manufacturing of the PBF-LB components made of AlSi10Mg

Parameter	Value
Scanning speed [mm/s]	1650
Laser power [W]	350
Layer thickness [µm]	30
Slicing stripe width [mm]	10
Hatch spacing [µm]	130
Rotation angle of scan pattern [°]	67
Base plate heating temperature [°C]	150

C. Application by Injection – Additive Manufacturing (IAM)
i Merging of PBF-LB component and aluminum round bar and concentric alignment through centering surface
ii Injection of adhesive at one injection point
3. Hardening: 7 days at 23 °C and 50% humidity, stored vertically

3.2 Test implementation

The static tensile tests were carried out on a 600 kN servo-hydraulic testing machine (*Schenck Trebel*). Wedge grips fixed the joints over a clamping length of 100 mm (Fig. 1). An external video extensometer (*LIMESS RTSS*) was used to measure the strain through the change in length between two sticky markers at a distance of L_0 = 8 mm (Fig. 1). To steadily increase the force on the test joint, the testing machine was operated force controlled with a constant test speed of 1.5 mm/min. The test results are documented in form of a stress–strain diagram, from which the maximum measured nominal shear stress (fracture stress) of each joint was evaluated. The designs feature an identical adhesive surface area of 2641.5 mm^2.

4 Results and discussion

Referring to the de-powdering procedure of IAM-samples, the methodological steps depicted in Fig. 3 show to be sufficient to completely remove trapped powder from the inner channels.

As the majority of residual powder was removed in the course of Step 2, it can be concluded that it is necessary to apply mechanical excitation to the components in order to loosen up powder residues which can subsequently be removed by suction. It is possible to transfer the mechanical excitation from the ultrasonic bath through the build plate to the components without soaking them. Since Step 3 has a negligible effect on the residual powder weight compared to Step 1 and Step 2, it can be deduced that soaking of the components to remove residual powder from inner channels is not essential.

Assuming a gaussian normal distribution the mean value ($n = 4$) of the fracture stress (maximum measured nominal shear stress) and standard deviation (SD) according to the adhesive application via injection into AM inner channels can be evaluated to $\tau_{IAM} = (31.6 \pm 0.7)$MPa (Fig. 4). The fracture stress of components where the adhesive was applied via injection into geometries manufacturable by subtractive machining results in $\tau_{ISM} = (28.7 \pm 2.3)$ MPa and the fracture stress of components where the adhesive was pre-applied to the adhesive surfaces yields to $\tau_{PA} = (8.9 \pm 0.2)$ MPa.

To determine if the mean values are significantly (significance level of 5% was chosen, i.e. $\alpha = 0.05$) different from each other, an independent one-tailed homoscedastic t-test was executed. The p-value comparing the mean values derived from the adhesive application by injection and PA calculates to $p_{IAM-PA} = 0.00031$ and the p-value comparing the mean values derived from IAM and ISM calculates to $p_{IAM-ISM} = 0.042$. As $p < \alpha$ in both cases, this proves the statistical significance of the difference between the mean values of the test results.

Assuming that the bonding strength corresponds to the fracture stress, it can be concluded that the bonding strength of IAM exceeds the bonding strength of ISM by 10% and the bonding strength of PA by 255%.

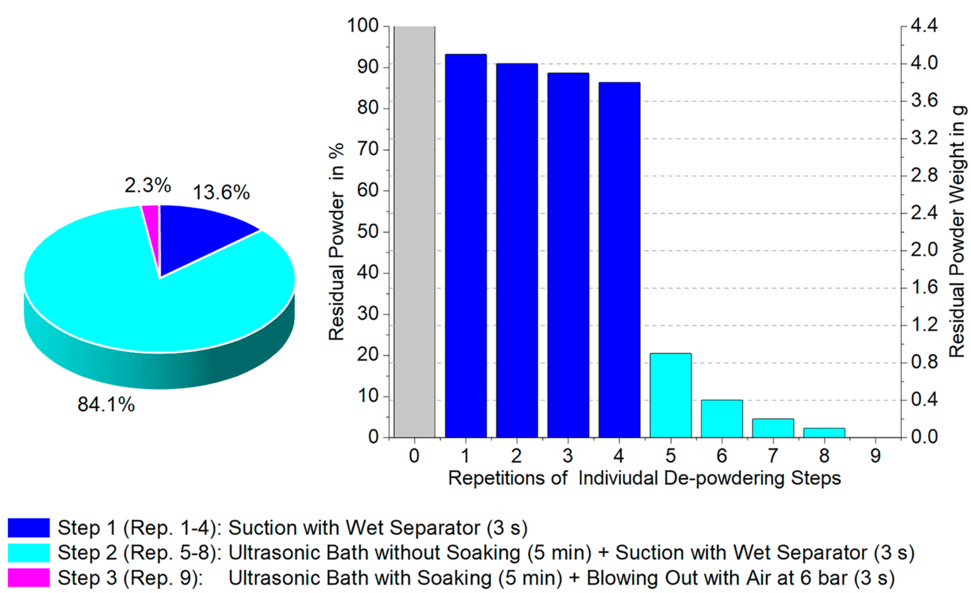


Fig. 3 De-powdering procedure of inner channels quantified by weighing methods

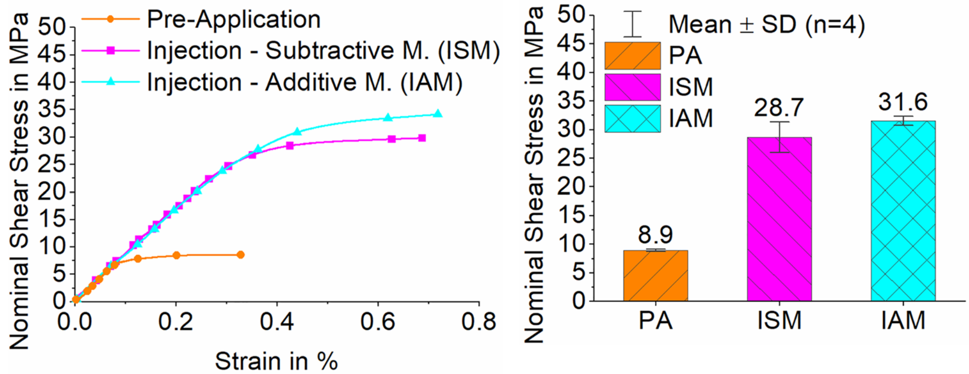


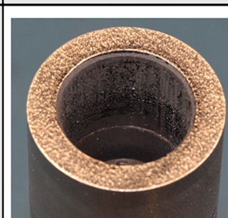
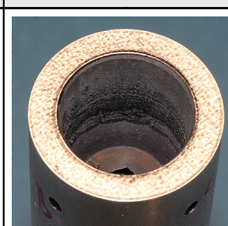
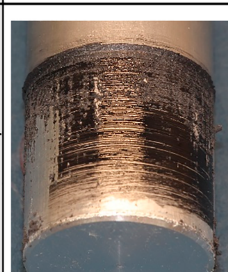
Fig. 4 Stress–Strain diagram of 3 exemplary test joints (left) and evaluation of the fracture stress and standard deviation (SD) of all tested joints (right)

The fracture patterns of the failed test joints correlate with the resulting bonding strength obtained from the static tensile tests. The resulting failure mode of PA can be categorized as a special cohesion failure (SCF). The circumferential pattern in the adhesive layer adhered to the aluminum round bar (Fig. 5, left) clearly shows that when the joining partners were merged with a rotating motion, proper mixing of the adhesive pre-applied to the respective joining surfaces did not occur. The majority of the adhesive was pushed out of the fill gap when the joining partners were merged, resulting in adhesive underdosing. In the case of ISM the resulting failure mode is adhesion failure (AF). As the failure location shifts from the adhesive surface of the inner adherent to the adhesive surface of outer adherent at the location of the groove for circumferential adhesive distribution (Fig. 5, center), it is conceivable that distribution geometries introduced directly into the adhesive surface weaken the bond for locally thickening the adhesive fill gap. Test joints where the adhesive was applied according to IAM failed adhesively (AF) to the aluminum round bar in the lower part of the overlap (70%) and cohesively (CF) in the upper part of the overlap (30%) (Fig. 5, right). Adhesion failure at the adhesive surface of the outer adherent did not occur.

If the process reliability is assessed according to the lowest SD of the fracture stress, the most reliable bonding process was achieved by pre-applying the adhesive to the adhesive surfaces. This is contrary to the author's expectations, as this approach requires most manual working steps and therefore offers more scope in execution than applying the adhesive via injection. However, this behavior can be explained by the fact that the single manual working steps involved in the bonding process of the four test joints were taken directly one after another with highest care under laboratory conditions and therefore the approach is not capable of reflecting industrial practice.

In terms of handling expense, it can be concluded that injection into multiple inlets (ISM) results in most adhesive waste. The adhesive was injected crosswise into the

Fig. 5 Exemplary fracture patterns and respective failure modes of test joints after the static tensile tests

Application Concept	PA	ISM	IAM
PBF-LB-Component (Outer Adherent)			
Aluminum Round Bar (Inner Adherent)			
Failure Mode	SCF	AF	AF(70%) + CF(30%)

first two through holes of the ISM-component one after the other until it leaked from the overlap ends above the respective through holes. As the adhesive propagates concentrically to the through holes within the fill gap, the adhesive injected into the last two through holes meets the already injected adhesive before leakage from the overlap end. While the adhesive continues to be conveyed to the end of the overlap, part of the adhesive already injected leaks from the adjacent free-standing inlets. This effect is intensified by the distribution groove introduced to the joining surface, into which the inlets to the adhesive fill gap open. Weighing the adhesive cartridge before and after the adhesive was applied shows an excess consumption of 254% compared with IAM and 64% compared with PA.

5 Conclusion

It could be shown that inner channel geometries manufactured by the PBF-LB process can be used to transport and convey the adhesive to the fill gap prescribed by the aligned adherents when the adhesive is injected into an affiliated inlet. The successful implementation of this approach depends on the ability to remove the residual powder from the inner channels. It has been demonstrated that the mechanical excitation needed to loosen up residual powder can be applied to the components by means of an ultrasonic bath without actually soaking the inner channels.

Compared to the traditional approach towards adhesive application, where the adhesive is pre-applied to the adhesive surfaces (before the adherents are merged), the bonding strength can be increased by 255% when injecting the adhesive into inner channels. The latter also leads to reduced manufacturing time and adhesive waste, increasing the potential for automation in industrial applications. The highest process reliability under laboratory conditions was found for the adhesive pre-application. To assess the process reliability with respect to industrial practice, a study is planned in which multiple participants are going to manufacture test joints using different adhesive application concepts. It is expected that the process reliability affiliated to the adhesive pre-application will decrease disproportionally compared to the adhesive application into inner channels, as the latter offers less scope in execution.

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Declarations

Conflict of interest For this research, there is no conflict of interest for all authors.

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