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Laser droplet brazing for electrical contacting of composite materials with integrated active elements

Ulf Quentin[a,b,c,*], Johannes Heberle[b,c], Carolin Held[a], Michael Schmidt[a,b,c]

[a]*Bayerisches Laserzentrum GmbH, Konrad-Zuse-Straße 2-6, 91052 Erlangen, Germany*
[b]*Institute of Photonic Technologies, University of Erlangen, Paul-Gordan-Staße 3, 91052 Erlangen, Germany*
[c]*Erlangen Graduate School in Advanced Optical Technologies, Paul-Gordan-Straße 6, 91052 Erlangen, Germany*

Abstract

To be used as actuators or sensors, piezoceramic components have to be electronically contacted. A temperature stable connection can be achieved with brazing techniques. Since piezoceramics are susceptible to damage by high temperatures and temperature gradients, it is important to control the energy input in the brazing process. Therefore, we use a laser droplet brazing method which allows for precise contacting of piezoceramics and avoids thermal damage. The influence of the laser parameters on the brazing process and the contacting accuracy is presented in this paper.

Keywords: laser brazing; electrical contacting

1 Introduction

The integration of piezoelectric components into structural lightweight parts bears the potential of sensing or active damping of mechanical vibrations or can even be utilized for energy harvesting. Ceramic composite adaptronic modules which can be used for these purposes have to be embedded by die casting. In this

* Corresponding author. Tel.: +49-9131-8523236;
E-mail address: ulf.quentin@lpt.uni-erlangen.de

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production process, the piezoelectric modules are exposed to high temperatures up to 600 °C. Therefore, an electrical contacting method is needed which can withstand such a high thermal load. Furthermore, the high pressure during die casting requires the joint height to be very small, preferably smaller than 200 µm. Contacting by welding is not applicable in this case due to the low thickness of the contact pads. Soldering does not provide a temperature stable connection, whereas conventional brazing induces too high thermal gradients which lead to thermal damage and cracks in the piezoceramic material. Thus, a suitable micro-brazing method has to be developed which meets the above-mentioned requirements.

A promising way to limit the energy input into the substrate is to braze with single droplets. In the last years, it has been attempted to melt droplets off of wires with laser radiation [1-4]. Although this approach is capable of generating braze connections, the accuracy of both the droplet size and the positioning on the substrate is limited. Therefore, we pursue an alternative approach in which the mass of the braze droplet is controlled by using spherical preforms which are positioned by a conical nozzle. The diameters of the braze preforms are slightly larger than the nozzle outlet diameter so that the preform is held in a defined position. Since the braze ball blocks the nozzle outlet, it enables a nitrogen pressure to build up in the nozzle. A single laser pulse melts the braze preform which is then pressed out of the nozzle by the nitrogen to contact the substrate. In this way, the substrate is not heated entirely and the energy input can be controlled very precisely. A similar setup has already been used for laser droplet soldering [5,6]. Fig. 1 depicts the principle of this process.

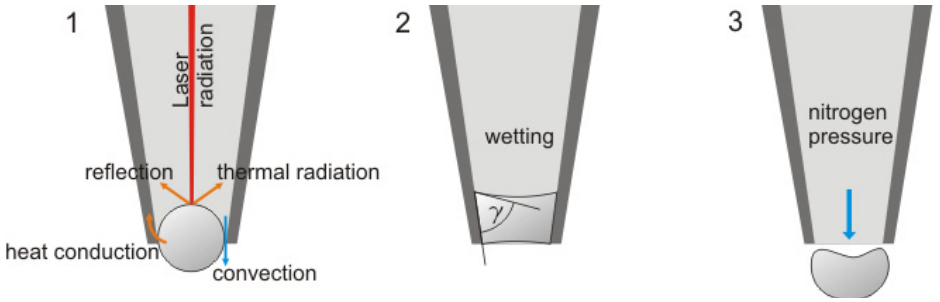

Fig. 1. Principle of laser droplet brazing with spherical preforms

2 Experimental setup

The experimental setup used for the investigations on the process is presented in fig. 2. A single braze sphere (Cu89Sn11, d=600 µm) is introduced through the ball feed into the WC/Co nozzle and seals the nozzle outlet. The ball feed opening is sealed as well and a nitrogen pressure of 100 mbar to 140 mbar is built up. The IPG Ytterbium-YAG Fiber Laser YLR-200-SM with a wavelength of λ=1070 nm, a maximum power of P_{max}=200 W and a beam diameter w=6.9 mm is focused by a lens with a focal length of either f=150 mm or f=75 mm to create a laser spot with a diameter of d_{spot}=35 µm on the braze ball surface. The substrate used for the brazing experiments is a LTCC (low temperature cofired ceramic) with screen-printed silver contact pads with a thickness of d_{cp}=20 µm. The distance between the nozzle and the substrate is usually d_{nozzle}=1.

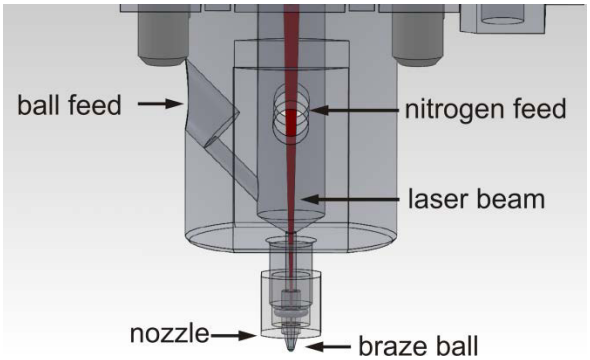

Fig. 2: Experimental setup

3 Experimental results

3.1 Parameter

We investigated the influence of the laser parameters pulse duration, pulse energy and focusing length of the lens. The focal distance was changed from 150 mm to 75 mm, while pulse energies from 6.0 J to 8.0 J and pulse durations between 50 ms and 100 ms were applied. The effect of pulse duration and energy is shown in Fig. 3. The resulting processes can be divided into three classes: Class one is a successful brazing process in which the braze preform is completely molten and detaches completely from the nozzle. In these cases no residues remain and the brazing droplet is positioned on the substrate, wets it and forms a connection upon solidification. The class one results are shown in Fig. 3 as green diamonds.

In case the energy input was not sufficient to completely melt the braze preform, the nozzle can be blocked by the partly molten braze material. This can occur when the pulse energy is simply too low or the pulse duration is too long so that a significant amount of the energy is lost via heat diffusion before the braze ball is entirely molten. In this case, the braze material wets the surface of the nozzle and can only be removed by etching. Class two is represented by blue squares in Fig. 3.

If the pule energy is rather too high than too low, or the pulse duration is too short, it leads to a very high intensity which can yield vaporization on the surface of the braze preform. This causes splatters in the nozzle and leads to braze residues. The vaporization occurs before the braze ball is completely molten and the preform does not detach completely from the nozzle. The residues influence the subsequent brazing: the braze ball cannot seal the nozzle well enough; the nitrogen will leak which prevents the required pressure to be built up. Additionally, the leakage can cool the braze ball and impede homogenous heating and melting. If the preform is molten, the asymmetric gas flow can also influence the path of flight and prevent the braze droplet to contact the pad in the desired location. This class is represented by red triangles in Fig. 3.

For melting the braze preform completely and detaching it from the nozzle, a minimal pulse energy of 7 J is necessary. This value is dependent on the pulse duration due to diffusive heat transport to the nozzle and the surrounding media. Longer pulses naturally need a higher energy to fully melt the braze preforms.

The before-mentioned parameters are obtained with a focusing lens of f = 150 mm. Due to the long focal length, the Rayleigh range is also quite high (900 µm). In some cases, this can lead to damaging of the substrate by the laser, since the beam is not sufficiently divergent and still irradiates the substrate with a considerably high intensity. In this case, the pulse duration cannot be decreased to prevent the laser from irradiating the substrate after the braze ball is molten, because the melting durations of the preforms fluctuate and cannot be controlled precisely. In order to avoid incomplete melting of the braze ball and clogging of the nozzle, the pulses have to be kept longer. Fig. 4a shows a cross-sectional view of a droplet brazing. It can be

seen that the height of the braze material on the substrate is uneven but that it formed a sufficient connection to the substrate. As can be seen in Fig. 4b, however, the center of the brazing was damaged by the laser. In some more extreme cases, the whole substrate can be even drilled through.

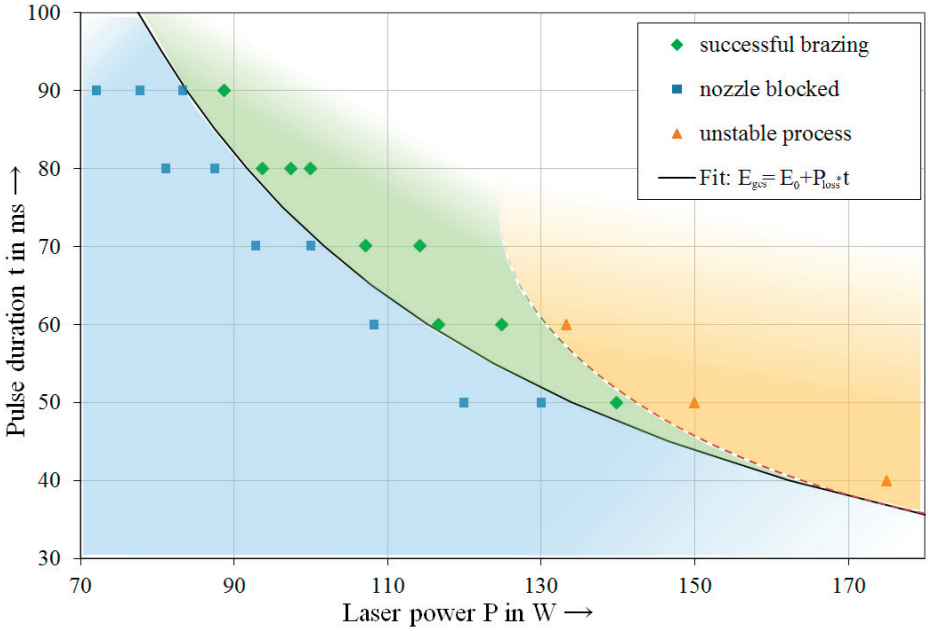

Fig. 3. Process window for laser droplet brazing. The blue squares represent a blocked nozzle due to insufficient energy input. The red triangles represent an excessive laser power which leads to vaporization and splatters. Succesful melting and detaching of the braze material is indicated by the green diamonds.

Fortunately, damage to the substrate can be avoided by using a lens with a shorter focal length. The higher numerical aperture leads to a higher cone angle of the focused laser beam which can result in clipping of the beam at the nozzle entrance. Additionally, a shorter focal length also requires the lens to be placed closer to the nozzle. For our experimental setup, a 75 mm lens has the shortest focal distance which can be employed without clipping. Since the smaller focal spot of a 75 mm lens compared to 150 mm is not advantageous in this process, the laser beam is not focused directly onto the brace ball, but rather 350 µm above it. This leads to irradiation of a diameter of 35µm on the braze ball and also prevents the substrate from being damaged by the laser.

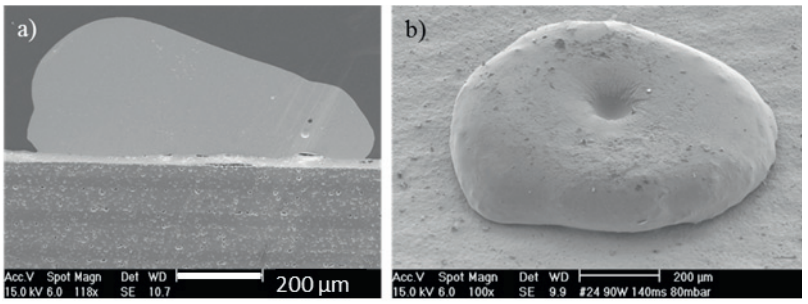

Fig. 4. a) Cross-sectional view of a brazing; b) Laser damage on a brazing due to pulse duration and Rayleigh range being too long.

3.2 Lateral Accuracy

Beside the laser parameters and the nitrogen pressure, the distance from the nozzle to the substrate has an important influence. The experiments described above were conducted with a distance of 1 mm. At this configuration, the flight path of the braze droplet is controllable and the droplet hits the substrate centered with regard to the nozzle. Fig. 5 shows frames from a high-speed video. It can be seen that the droplet exits the nozzle on axis and forms the desired flat connection. The total time of heating the braze preform, detaching it from the nozzle and contacting the substrate is 85 ms to 90 ms. In the first 80 ms the droplet is heated and molten; the flight time of the droplet is only approximately 3 ms.

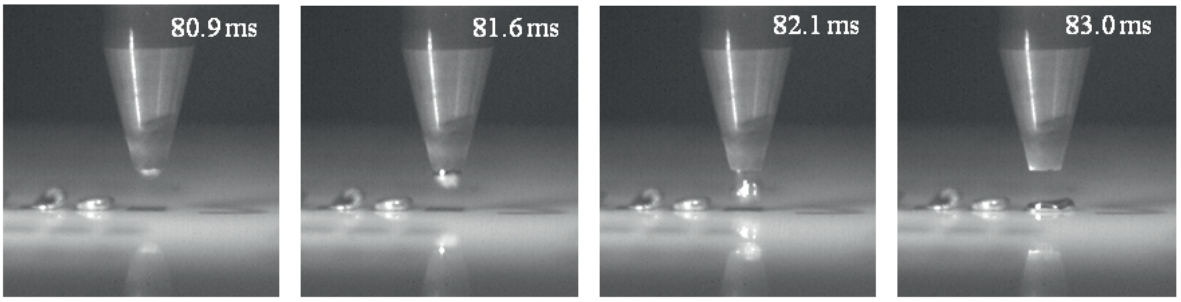

Fig. 5. Still frames from the high-speed camera recording showing the detachment and wetting of the braze droplet on the metalized ceramic substrate. The process parameters used were P = 80 W, tp = 90 ms, p_{N2} = 100 mbar.

In some cases, however, the braze ball has a small momentum to one direction and its impact position on the substrate is slightly off center. This can be seen in Fig. 6, where the braze ball does not detach homogeneously from the nozzle. The nitrogen pressure breaks through the liquid droplet on one side of the nozzle and gives rise to a fluid flow at that side. This leads to a rotational momentum of the droplet which finally leads to an angled, off-center flight path. This does not only result in a deviation of the braze position from the center of the contact pad, but can also form a distorted, asymmetric brazing.

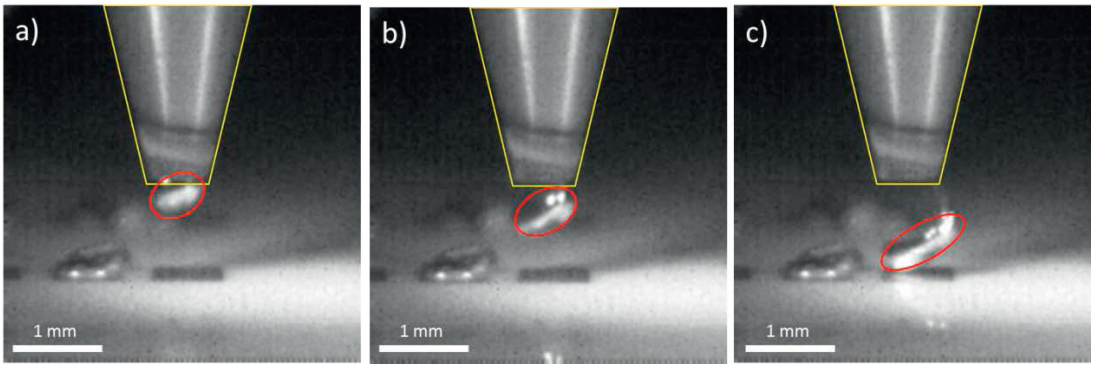

Fig. 6. Asymmetric detachment of the braze droplet. A rotational momentum of the droplet affects its flight path and leads to an off-center connection on the substrate

The larger the distance from the nozzle to the substrate, the larger is the deviation of the braze location on the substrate from the center of the contact pad. We measured this deviation for four distances from 1 mm to

2.5 mm with 10 measurements each. The mean distance of the braze connection center to the contact pad center is plotted in Fig. 7, together with the standard deviation. Naturally, the deviation increases with increasing distance.

In case of a distance of 1 mm, the mean deviation of the brazing center to the intended location is 130 µm, with a standard deviation of ±57 µm. With the brazings being approximately 700 µm to 800 µm in diameter, this is accurate enough to guarantee sufficient positioning for over 99.7 % (3σ) of all brazings. Increasing the distance to 1.5 mm does already increase the mean positioning deviation to 310 µm. This means that only 50 % of the brazings are positioned well enough, which is already not acceptable for a production process.

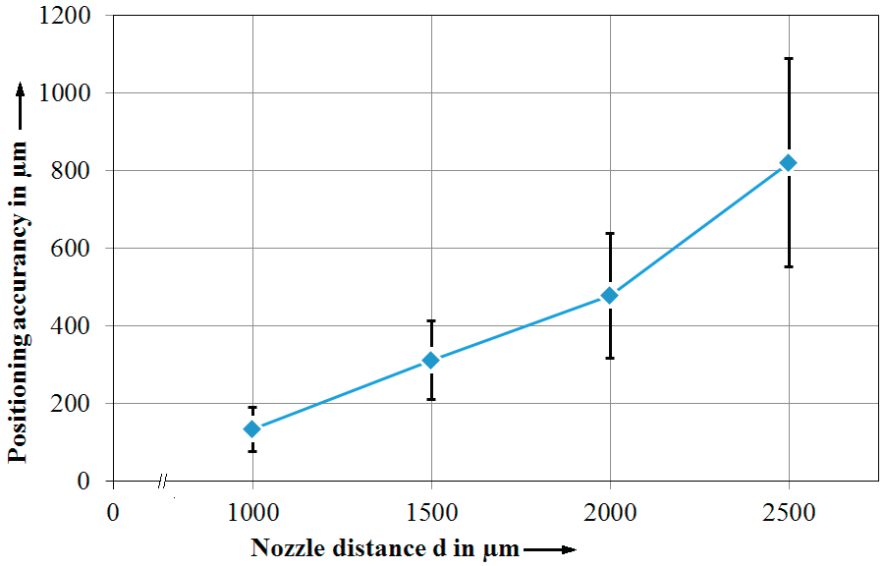

Fig. 7: Mean deviation of the center of the brazing to the center of the contact pad. Naturally, the deviation increases with increase distance from the nozzle to the substrate (number of measurements per data point n=10).

The off-center detachment of the braze droplet could be due to residues in the nozzle which prevent the braze preform to be held precisely in the center of the nozzle. In this case, the preform would not seal the nozzle well enough, which leads to fluid flows that can influence the flight path. Another reason could be small differences in the heating of the braze preform, e.g. by a not perfectly aligned laser beam. If the temperature distribution across the braze ball is uneven, the ball melts faster on one side and also reaches a lower viscosity, thus allowing the nitrogen to break through more easily. However, this has to be confirmed experimentally in the future.

3.3 Height of the brazed joints

The height of the brazings has to be approximately 200 µm or smaller. This is not only necessary to keep the piezoceramic components small and flat; a flat brazing is also much more durable during casting of the modules. We measured the height of several joints (4 per parameter set) which were obtained by using different nitrogen pressures. The results are shown in Fig. 8. As can be seen in the diagram, there is a correlation between the nitrogen pressure and the height. At 110 mbar, the joints are 205 µm high on average. The average height decreases to approximately 160 µm for 130 mbar and 140 mbar.

Although the average heights meet the requirement of being smaller than 200 µm, they are not yet sufficient for the desired application, since the measurements represent the mean height across the surface of

the brazings. All of the measured brazings locally exceed the 200 µm limit. Therefore, they are not sufficiently flat and even. A further increase of the nitrogen pressure does not help in this case, since it does hardly decrease the mean height of the brazings and leads to an even rougher surface.

Furthermore, the main function of the nitrogen pressure is to enable and assure complete and residue-free detachment of the braze droplets from the nozzle. Using the pressure to influence the joint height is therefore not appropriate. To decrease the height, it would be much more suitable to use smaller braze preforms. This has not been tested yet since the currently available nozzles are too large for smaller preforms.

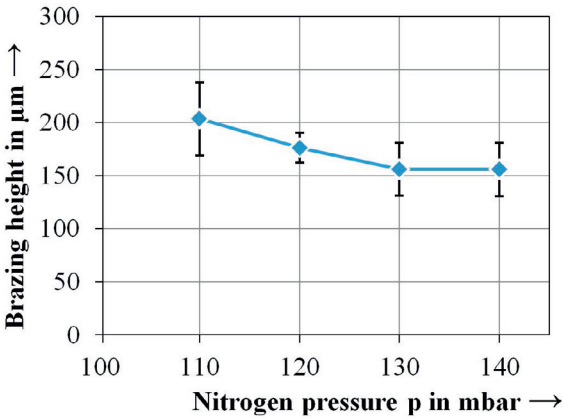

Fig. 8. Mean height and standard deviation of the brazed joints depending on the nitrogen pressure (n=4)

4 Conclusion and outlook

Laser droplet brazing is a capable method of generating temperature stable connections on piezoceramic components. The limited energy input by using braze preforms keeps the thermal load on the ceramics to a minimum and therefore prevents cracks. However, the laser pulse energy and duration used to melt these preforms have to be controlled precisely to ensure complete melting without vaporization of the braze material. If the laser power is not high enough, the braze preform will not melt completely and block the nozzle. If it is too high, vaporization will lead to splatters and braze residues will remain in the nozzle.

Even with optimal laser parameters, it cannot be guaranteed that the braze droplet leaves the nozzle exactly on axis. The path of flight will be angled most of the time which results in a deviation of the brazing position to the intended spot. This deviation increases with an increasing path of flight. Therefore, the distance between nozzle outlet and substrate has to be kept at a minimum. Our measurements have shown that a distance of 1 mm provides the desired accuracy, whereas the brazing position deviation in case of distances of 1.5 mm and larger becomes unacceptably high.

The reason for the off-center path of flight of the braze droplets has not been conclusively examined yet. For clarification, we will investigate the influence of the brazing accuracy on the alignment of the laser beam and on the nitrogen pressure. Furthermore, we will measure the strength of the brazings in dependence of different nitrogen pressures and pulse energies to reach a global optimum in the parameter space.

Moreover, slightly smaller braze preforms would be advantageous to decrease the height of the brazed connections. Since the current nozzles are too large to hold smaller preforms, matching nozzles have to be manufactured.

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