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Modelling of droplet detachment in the laser droplet brazing process

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ABSTRACT

The laser droplet brazing process has been recently experimentally considered for the electrical contacting of thermally sensitive components. In this process, a spherical brazing preform, placed in a tapering nozzle, is melted by a laser pulse, detached from the nozzle by a shielding gas overpressure, and deposited on the brazing spot. The detachment of the brazing droplet from the nozzle has been studied theoretically in this paper with the aim of providing guidance for the selection of the main process parameters, i.e. the gas overpressure and the droplet contact angle. The droplet detachment is described by two models: an algebraic droplet force balance model and a numerical isothermal two-phase fluid flow model. Using the droplet force balance based model, an algebraic expression defining the dependence of the maximum gas overpressure before droplet detachment on the droplet contact angle was obtained. The numerical model was used to determine the droplet detachment occurrence in terms of the main process parameters. Additionally, the nonlinear dependencies of the time of droplet detachment, the detached droplet velocity and vertical position, and the droplet shape on the gas overpressure and the brazing droplet contact angle were defined, and can be used for process parameter selection. It was also found that the detached droplet shape is influenced, beside the gas overpressure and the droplet contact angle, by oscillation of the droplet, which can be significant at droplet contact angle values of less than 75°. Based on comparisons of the modelled and experimental results of droplet detachment time, vertical position of the detached droplet, and its shape, it was concluded that the contact angle of the CuSn11 brazing material on the WC/Co nozzle was, in the experiments, near 105°. Furthermore, comparisons of the results indicated that the laser melting phase of the preform significantly influences droplet detachment, and should therefore be taken into consideration for the improvement of the numerical model.

1. Introduction

The desired weight reduction of transport vehicles is often achieved by introducing thin-walled metal structures, which can, however, lead to the undesired vibration of a structure (Kollmann et al., 2006). In order to be able to sense and actively control the vibration, piezoelectric components are integrated into such structures. If the integrated components are coordinated by an automatic control system, then the resulting structure is called a smart structure. A review on the piezoelectric sensing, actuation and control of such smart structures has been presented by Irschik et al. (2010). One of the methods for integrating piezoelectric components into metal structures is to cast them as inserts. Recently, Schwankl et al. (2013) reported the damage-free integration of multilayered low temperature cofired ceramic (LTCC)/PZT components by high pressure die casting, using the standard alloy 226 D.

Integration by high pressure die casting requires that the connections between the piezoelectric components and the electrical circuits be both mechanically and thermally stable, so that they can withstand the die casting process where the temperatures up to 600 °C are reached. For this reason soldering cannot be used for the realization of such connections. Additionally, the LTCC substrate is susceptible to cracks when exposed to high thermal gradients. Consequently, conventional welding and brazing, too, are not applicable. In order to realize successful electrical connections on a

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LTCC/PZT module, a method is needed that would not only introduce a low thermal stress on the LTCC substrate, but also produce connections that are thermally stable at temperatures of up to 600 °C. Additionally, the maximum height of the contact is limited to 0.2 mm (Held et al., 2012) in order to avoid damage during casting.

Albert et al. (2011) proposed a non-contact laser droplet joining process, as described by Govekar et al. (2009), for the realization of thermally stable connections on a LTCC/PZT module. In this process, a laser pulse is used to melt the end of a brazing wire and detach the molten droplet, which is then deposited onto the contact pad. The brazing joints are realizable, as reported by Albert et al. (2011), but the reproducibility of the joining is low due to uncontrollable variation of the droplet diameter.

To maintain the versatility and accurate control of the energy input by the laser beam, and at the same time to achieve control over the droplet diameter, Held et al. (2012) proposed a laser droplet brazing method that employs spherical brazing preforms. In this method, a spherical preform, placed in a vertical tapering nozzle, is melted by a laser pulse and then ejected through the nozzle by the shielding gas overpressure that is generated inside the nozzle.

In a preliminary experimental study of the laser droplet brazing process, Held et al. (2012) determined the process window for the laser parameters. They also reported observations of thermal crack damage to the nozzle. The estimated temperature variation of the nozzle leads to considerable thermal stress, which could bring into question the long-term stability of the nozzle. In a second experimental report, Quentin et al. (2013) studied the influence of the distance between the nozzle and the substrate on the lateral accuracy of droplet deposition, and the influence of the shielding gas overpressure on the brazing joint height. The above studies indicated a need to investigate the influence of different brazing alloys and nozzle materials which would result in different wetting conditions and a lower thermal stress in the nozzle due to the lower temperature of melting, as well as a need to investigate the influence of the shielding gas overpressure on the lateral position accuracy of the deposited droplet.

Detachment of the brazing droplet from the nozzle due to the shielding gas overpressure strongly influences the subsequent phases of the laser brazing process, including the droplet flight and deposition, where the lateral accuracy of droplet deposition, droplet – deposition spot wetting, and the corresponding height of the generated brazing joint are affected. For this reason the detachment phase has been studied in this work in order to gain a theoretical insight in the influence of the contact angle between the molten brazing material and the nozzle, as well as that of the shielding gas overpressure on the droplet detachment from the nozzle. The detachment phase of the process is characterized by the following output parameters: the occurrence and time of detachment of the droplet, as well as its velocity, position, and shape. The obtained results aim to provide some guidance in the selection of the brazing and nozzle materials, as well as the corresponding process parameters.

For this purpose, in the second section of the paper, the laser droplet brazing experimental system and process have been described in more detail. In the third section, an algebraic and a numerical model of detachment are presented. The algebraic model describes the force equilibrium of a brazing droplet in a tapering nozzle. It takes into account the influence of the droplet contact angle and the shielding gas overpressure, and can provide estimates of the value of the maximum shielding gas overpressure at which the equilibrium state can still exist. The finite element numerical model of detachment describes the dynamics of the detachment, the results obtained being the time of detachment of the droplet, as well as its velocity, position, and shape. In the fourth section, the results of both models and the experimental results are compared and discussed.

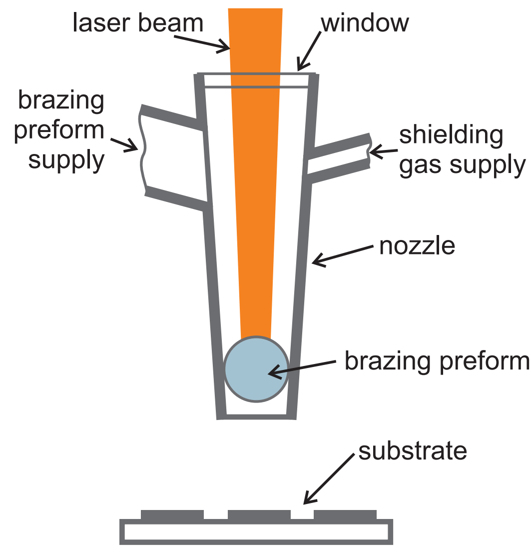

Fig. 1. Scheme of the laser droplet brazing system.

2. The laser droplet brazing experimental system and process

The laser droplet brazing system that was used in the brazing experiments is schematically shown in Fig. 1. The main part of the system is a WC/Co nozzle with a tapering angle of 3.7°, orifice inner radius r_0 = 0.297 mm, and outer radius R_0 = 0.353 mm. The top of the nozzle is closed by a glass window, which is transparent for the laser beam. On the nozzle sides are the apertures for the shielding gas and brazing preform supplies. A Ytterbium-YAG fibre laser, with a wavelength of 1070 nm and a maximum power of 200 W, is used as the energy source to melt the brazing preform. The laser generates a beam with a diameter of 6.9 mm, which is focused onto a spot with a diameter of 35 μm on the surface of the brazing preform of diameter 0.6 mm. In order to prevent oxidation, and to generate the required overpressure in the nozzle, nitrogen shielding gas is supplied at selected constant pressure provided by a pressure regulator. For the process visual characterization, a high-speed video camera was used to record the region near the nozzle orifice. The camera acquired 13,029 frames per second at 256 × 256 pixels per frame and a resolution of 17 μm per pixel.

In the case of the selected preform and nozzle materials, the main process parameters are the laser pulse power and duration, and the shielding gas overpressure. The laser brazing process starts with insertion of the spherical brazing preform into the nozzle through the insert aperture. After this insertion, the aperture is closed to prevent leakage of the shielding gas. The shielding gas supply is then set to a selected constant overpressure value. Since the preform blocks the nozzle orifice, the shielding gas overpressure builds up in the nozzle and holds the preform in place. After the preform has been placed in the nozzle, the process of laser droplet brazing phenomenologically consists of the following sequential phases: melting of the spherical preform by a laser pulse, detachment of the molten brazing material from the nozzle in a form of a droplet due to the shielding gas overpressure, the flight phase of the brazing droplet, and the deposition of the brazing droplet on a substrate.