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Methodology for analyzing the influence of contact temperatures in laser beam brazing

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Abstract

In laser beam brazing, the contact temperature between the brazing material and the substrate as well as the wetting behavior play decisive roles. Thus far, the process has been analyzed using model experiments via either droplet tests or tests with small amounts of brazing material pre-placed on the base material. While in the first case a comparatively high overheating of the molten brazing material is required to enable droplet formation, in the second case it is not possible to determine the emerging contact brazing temperature in the interface with sufficient accuracy. The current study presents a novel setup that can characterize the influence of the contact temperature on the laser beam brazing process. The setup enables the investigation of process temperatures slightly above the liquidus temperature of the brazing material and facilitates the surface temperature measurement of the brazing material shortly before contact generation.

Keywords: Laser brazing; Contact temperature; Joining; Wetting; Interface

1. Introduction

Brazing is a metal joining process in which a filler material is melted and subsequent wets the substrate materials present in solid form. During brazing, the characteristics of the wetting process are crucial for the quality of the brazing seam and are influenced by numerous factors. These include the material combination being used, the presence of oxide layers, and the temperature of the brazing and substrate materials (Koltsov et al., 2010). The understanding of the impact of the individual factors on the wetting process helps

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to increase the quality of brazing seams and for the development of new material combinations. Compared to conventional brazing techniques like torch or furnace brazing, laser beam brazing has short process times (Martinsen et al., 2015). For such short-time processes, which on the substrate side additionally have a small heating area, standard techniques for analyzing the wetting behavior are only applicable to a limited extent.

One approach to analyzing the wetting behavior in a laser beam brazing process is based on the sessile drop technique and uses small amounts of brazing material, which are placed on the substrate and melted by a laser beam. While different material combinations and amounts of brazing material can be investigated, this approach does not enable an independent variation and measurement of the droplet and substrate temperatures. Similar limitations occur for conventional bead-on-plate approaches (Gatzen et al., 2016). For this reason, an approach based on falling droplets was established by Gatzen et al., in which a droplet is created from a filler wire using a laser beam (Gatzen et al. 2014-1). The liquid metal droplets are detached from the filler wire by a short pull-back of the wire and then fall onto the substrate placed below. Using this approach, both the temperature of the droplet and of the substrate can be measured separately. Additionally, a preheating of the substrate can be carried out independently from the brazing material temperature. However, this approach is limited by the fact that a significant overheating of the brazing material must be present to ensure that the droplet falls after the wire retraction. Due to this, only comparatively high brazing material temperatures can be investigated. In the case of AlSi12, a droplet temperature above 1450 °C is necessary to assure the falling of the droplet, even though its liquidus temperature lies below 600 °C.

In laser beam brazing, it is crucial to remove the oxide layer from the substrate (Jia et al., 2015) as well as remove or break up the oxide layer of the brazing material (Gatzen et al., 2014-2); otherwise, the oxide layers will act as diffusion barriers and hinder the wetting process. To remove the oxide layer of the substrates, different methodologies have been established for different material combinations. While for the brazing of aluminum, fluxes are commonly used to remove the oxide layer and improve wetting (Markovits et al., 2003), a zinc coating on steel substrates also significantly increases its wettability (Vollertsen et al., 2011).

The current state of research shows that the wetting behavior during laser beam brazing is strongly influenced by the temperature of the brazing and substrate materials. To analyze the wetting process in laser beam brazing, sessile drop, bead-on-plate and falling droplet approaches are used. However, these approaches do not allow an individual variation of the brazing or substrate material temperatures, and they also require a high overheating of the brazing material. In this study, a methodology for the analysis of the influence of droplet and contact temperatures in laser beam brazing that does not include limitations on the droplet temperature has been developed. The functionality and reproducibility of the developed methodology are characterized for AlSi12 brazing material and zinc-coated steel substrates.

2. Experimental

An experimental model system was designed to create liquid metal droplets and bring different substrates into contact with them at specific droplet and substrate temperatures. This model system was utilized to create liquid metal droplets out of an AlSi12 filler wire with a 1.2 mm diameter using a laser beam as an energy source (see Fig. 1). After the irradiation of the filler wire by the laser beam for 2.2 s, the cooling curve of the formed droplet was recorded from below using a two-color pyrometer (IMPAC IGAR 12-LO MB22). The droplet thereby stayed connected to the filler wire. The pyrometer had a measuring range between 500 °C and 2200 °C and was operated with a measuring frequency of 500 Hz and a measuring spot size of 2.0 mm. The used laser (TRUMPF TruDisk 12002) had a wavelength of 1030 nm, a laser spot diameter of 1.4 mm in the axis plane of the filler wire, and was operated with a laser power of 1000 W. The AlSi12 filler wire was fed into the process chamber using a wire feeder (DINSE FD 100 LS) with a speed of 1 m/min. By varying the laser power, filler wire speed and irradiation time, the temperature and size of the droplets could be adjusted. The droplet formation as well as the cooling process were recorded using a high-speed camera (Phantom V5.1), filming in the y-direction through an observation window in the process chamber at 500 fps. The process was carried out in an argon atmosphere with an oxygen concentration below 100 ppm.

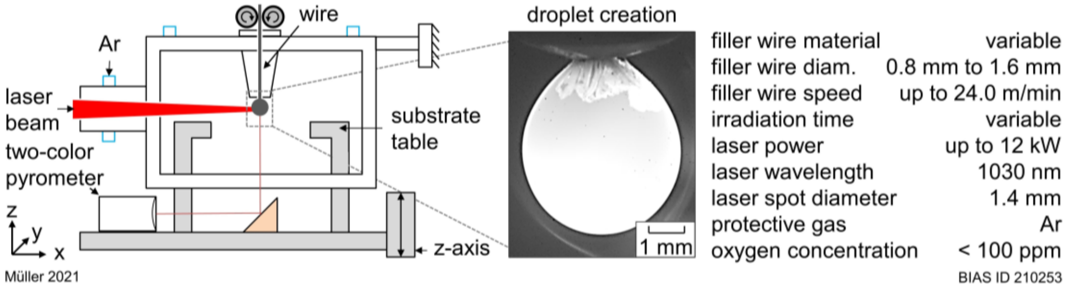

Fig. 1. An experimental model system for the creation of metal droplets and the measurement of the droplet temperature.

By positioning a substrate (DC04 +ZE50/50, thickness 1 mm) on the substrate table of the experimental model system, it was possible to bring the substrate into contact with the created liquid AlSi12 droplet after specific process runtimes utilizing a z-axis (see Fig. 2). Since the substrate was moved towards the droplet while the droplet remained in place, the droplet did not experience any additional dynamics up until the initial contact with the substrate. By using the time signal of the previously recorded cooling curve, the time at which the substrate was brought into contact with the droplet could be transferred into a droplet temperature that was present at the initial contact. Vice versa, the z-axis could be utilized to bring the substrate into contact with the droplet at specific droplet temperatures. To ensure that no laser radiation was reflected towards the substrate, resulting in an uncontrolled preheating, reflection shielding was positioned below the wire nozzle. This reflection shielding was removed from the process chamber as soon as the laser was turned off.

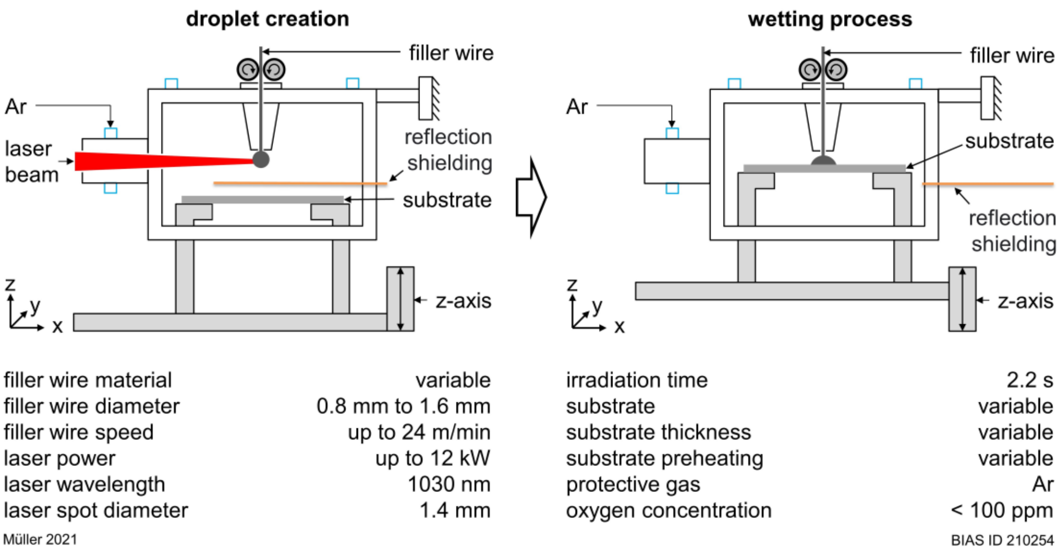

Fig. 2. An experimental model system for the creation of liquid metal droplets and a subsequent wetting process induced by a substrate being brought into contact with the droplet.

For a known brazing material temperature T_{Br} and substrate temperature T_{Su}, the contact temperature T_{Co} can be calculated using Eq. 1. The thermal effusivity e of the substrate and the brazing material can be calculated using Eq. 2, where λ is the thermal conductivity, ρ is the density and c_p is the specific heat capacity.

$$T_{Co} = \frac{T_{Br} \cdot e_{Br} + T_{Su} \cdot e_{Su}}{e_{Br} + e_{Su}} \quad (1)$$

$$e = \sqrt{\lambda \cdot \rho \cdot c_p} \quad (2)$$

3. Results

AlSi12 droplets were created using the experimental model system described in chapter 2 with a laser power of 1000 W and a filler wire speed of 1 m/min. The droplet temperature was recorded continuously from when the laser and wire feeder were switched on (process start) until it was assured that the droplet had cooled below its solidus temperature (see Fig. 3). Since the filler wire was initially positioned 5 mm above the axis of the laser beam, the irradiation time t_{irr} started 0.3 s after the initial process start. Once the filler wire reached the axis of the laser beam, the measured temperature rapidly increased to around 1600 °C. With increasing irradiation time, the fluctuation of the droplet temperature decreased. After an irradiation time of 2.2 s, the laser and wire feeder were turned off. From this point on, the droplet started to cool down to its solidus temperature of 573 °C in the solidification time t_{sol}, while still connected to the filler wire.

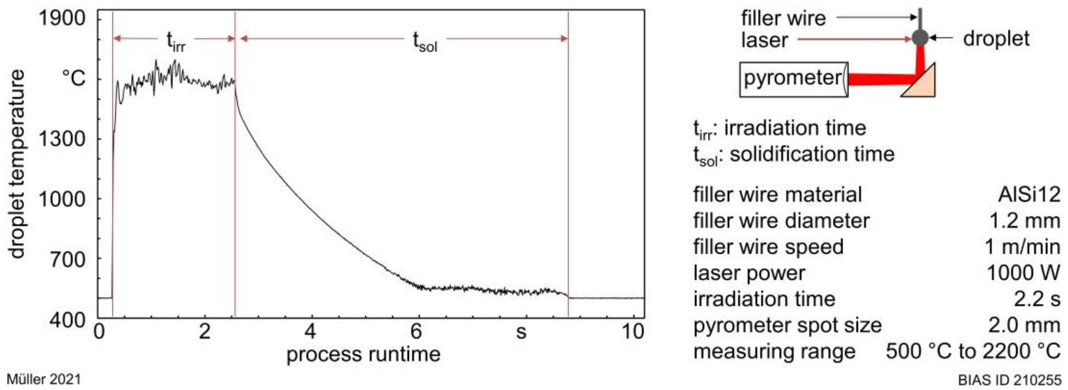

Fig. 3. Droplet temperature curve during the irradiation time t_{irr} and solidification time t_{sol} recorded using a two-color pyrometer aligned to the lower droplet surface.

The creation and cooling processes of the AlSi12 droplets were also recorded using a high-speed camera. After a process runtime of 0.3 s, the filler wire reached the axis of the laser beam and the irradiation started (see Fig. 4). At a process runtime of 1.0 s, cracks could be seen in the oxide layer present on the surface of the droplet. With a further increase in the process runtime to 1.5 s, the broken up oxide layer moved towards the upper part of the droplet, leaving an apparently oxide-layer-free surface on the lower part of the droplet. This behavior increased until a process runtime of 2.5 s, at which point the laser and the wire feeder were turned off. During the following solidification time, the oxide layer remained at the very top of the droplet while no new oxide layer formation could be seen on the remaining droplet surface. The droplet stayed connected to the filler wire over the full process runtime. At the beginning of the irradiation, up until a process runtime of around 1.5 s, slight lateral movements of the droplet could be seen.

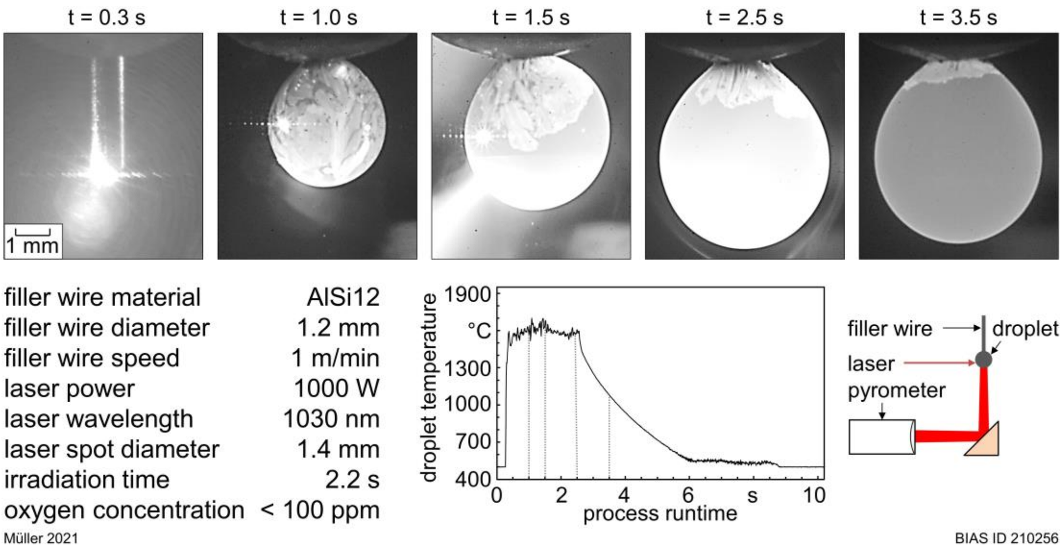

Fig. 4. Images of an AlSi12 droplet during the irradiation and solidification times.

To ensure the reproducibility of the measured cooling curves, ten individual droplets were created using identical process parameters. The median of the measured temperature curves as well as the positive and negative mean deviations from the median are depicted in Fig. 5. During the droplet creation, and hence during the irradiation time, the median droplet temperature as well as the deviations from the median fluctuated. Once the cooling process of the droplets began, the fluctuation of the droplet temperature declined significantly. At the beginning of the cooling process, at a median temperature of 1600 °C, the positive and negative mean deviations of the median were below 10 K.

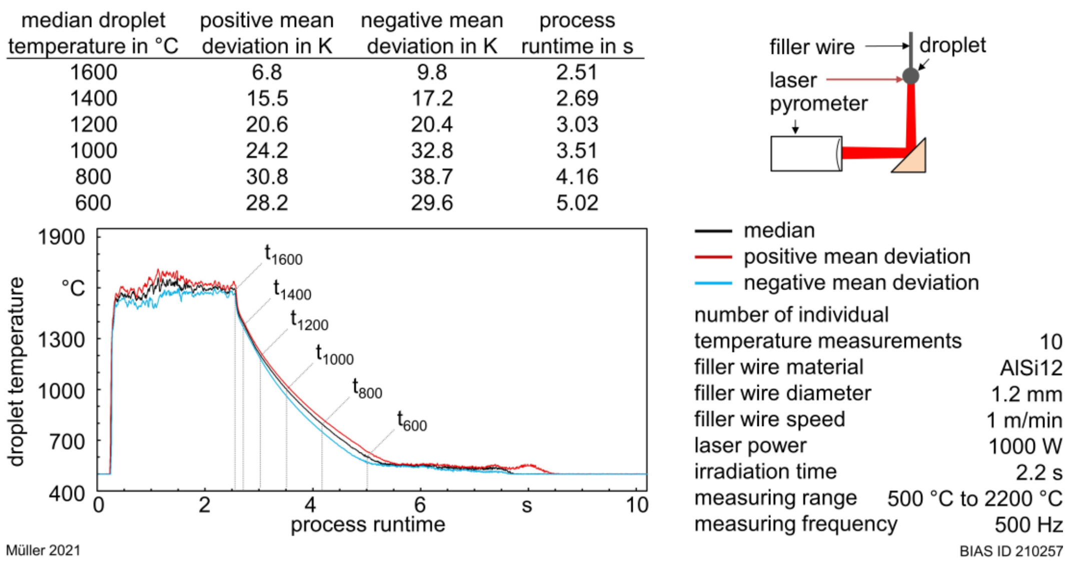

Fig. 5. Median and positive and negative mean deviations of the median for 10 consecutive droplet temperature measurements over the full irradiation and solidification times.

With increasing cooling time, the deviations from the median increased (see Fig. 5). At a median droplet temperature of 800 °C, the highest deviations from the median were present, which, however, were less than 40 K. It took 2.51 s for the droplet to cool down from its initial temperature of 1600 °C to a temperature just slightly above its melting interval of 600 °C.

The determined colling curve (see Fig. 5) was then used to bring room temperature DC04 +ZE50/50 steel substrates into contact with AlSi12 droplets of different temperatures (see Fig. 6). With a droplet temperature of 1000 °C at the initial contact, resulting in a contact temperature of 601 °C, the droplet did not wet the DC04 +ZE50/50 substrate upon contact. However, the droplet was slightly deformed due to being compressed between the wire nozzle and the substrate. No adherent connection between droplet and substrate was formed during this process. With a droplet temperature of 1400 °C at the initial contact, resulting in a contact temperature of 838 °C, the substrate was wetted by the droplet upon contact. While wetting the substrate, the upper part of the droplet stayed connected to the filler wire.

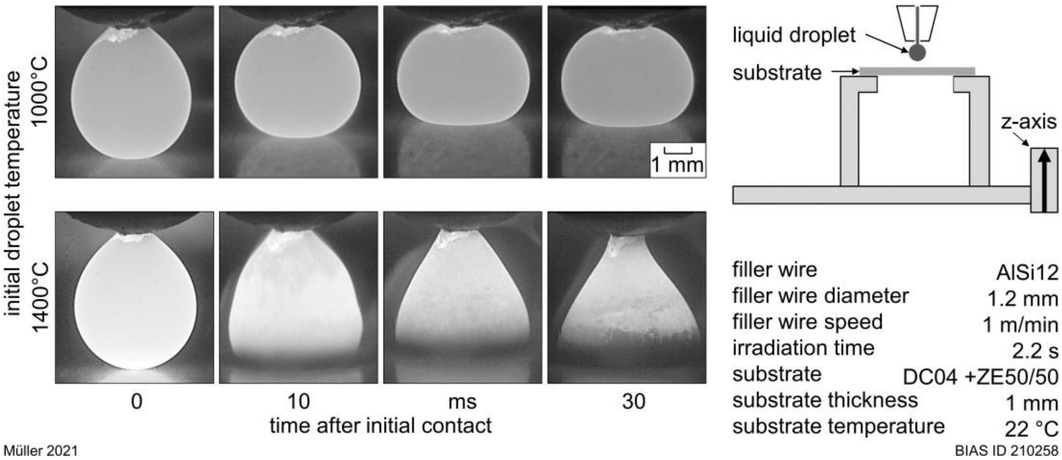

Fig. 6. Images of the wetting process after the initial contact between AlSi12 droplets with temperatures of 1000 °C and 1400 °C at contact and steel substrates having initially room temperature.

4. Discussion

Upon irradiation with the laser beam, the AlSi12 filler wire was constantly melted while forming a liquid droplet with increasing size. At the beginning of the irradiation time, the droplet showed slight lateral movements, likely due to the lateral laser beam impact (see Fig. 4). These lateral movements led to varying temperature measuring areas on the droplet surface, resulting in a fluctuation of the measurement of ± 100 K (see Fig. 3). With increasing irradiation time, the temperature fluctuations reduced due to the increasing weight of the droplet, resulting in a reduction in the lateral movements. Once the laser was turned off, a uniform cooling curve was recorded. Due to the expansion of the droplet, the oxide layer, initially present on the filler wire, was broken up (see Fig. 4), after which it was drawn towards the upper part of the droplet due to thermocapillary convection. As a result of an oxygen concentration of below 100 ppm in the process chamber, no new significant oxide layer formation was observed during the solidification time.

Due to the comparatively high fluctuation of the temperature measurement at the beginning of the irradiation of the individual droplets, the mean deviation of the median droplet temperature was also comparatively high in this timeframe (see Fig. 5). Likewise, due to the fluctuations of the temperature measurement of the individual droplets, the deviation of the median droplet temperature also reduced with increasing irradiation time. Once the laser was turned off, only minor mean deviations from the median of below 10 K were present at a median droplet temperature of 1600 °C. This proves the high reproducibility of the droplet creation process. The longer the droplet cools down, the higher the temperature deviation from the median becomes. However, even after cooling down to 600 °C, the mean deviation was still within ± 5% of the measured median value. The increasing temperature deviation with increasing cooling time could be explained by a variation of the contact area between the filler wire and the wire nozzle for the individual droplet creation processes. This could result in a slightly different degree of heat dissipation through the filler wire. While the methodology for analyzing the influence of different process parameters on the wetting behavior in laser beam brazing based on falling droplets is limited to droplet temperatures above 1450 °C (Gatzen et al., 2014-1), the here-developed methodology shows no limitations regarding the usable droplet temperatures.

If a substrate is brought into contact with a droplet at a droplet temperature of 1400 °C, the droplet wets the substrate upon the initial contact while staying connected to the filler wire. At droplet temperatures of 1000 °C, the contact temperature (601 °C) lies only slightly above the melting interval of the brazing material. Due to this, the wetting process between the droplet and the substrate is hindered and no connection can be formed. Even though no wetting occurs, the droplet is only slightly compressed between the wire nozzle and the substrate. Contrary to the methodology based on falling droplets (Gatzen et al., 2014-1), the methodology developed here hence allows the minimization of additional dynamic influences on the wetting process upon contact between the substrate and the brazing material.

5. Summary

- Due to thermocapillary convection, AlSi12 droplets can be created with an apparently oxide-free surface that remains in such a way during the cooling of the droplet.
- Reference cooling curves can be used to bring AlSi12 droplets and steel substrates into contact at droplet temperatures between 1600 °C and 600 °C with high accuracy. The highest mean deviation of the median droplet temperature occurring for ten cooling curves is below 40 K.
- Since the developed methodology enables an individual variation of the droplet and substrate temperature, the influence of different contact temperatures on the wetting process can be analyzed. Compared to the methodology using falling droplets, dynamic influences on the wetting process can be significantly reduced.

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