Lasers in Manufacturing Conference 2019

Keyhole Brazing with Two-Dimensional Laser Irradiation Patterns

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Abstract

Laser brazing is often used to join parts in the field of view because it offers good seam quality. In the case of laser brazing with aluminum- or copper-based brazing materials, the absorption is low when applying modern fiber and disk lasers with approx. 1 µm wavelength, depending on the material, since a simple Fresnel absorption takes place at the surface. The keyhole approach (formation of a vapor capillary), which is known from deep penetration laser welding, can also be used to increase absorption in brazing by carrying out a kind of deep penetration laser welding in the brazing material. To prevent a melting of the substrate material, the melting process must be limited in the wire by adjusting the penetration depth. This is realized through an oscillation of the laser beam. In this study, two-dimensional laser irradiation patterns were applied to keyhole brazing. In addition to the circular oscillation, a kind of eight-shaped strategy was compared with the transversal linear sinusoidal oscillation. The linear and the special eight-shaped oscillation strategy have turning points in the movement, which lead to local higher time-averaged power densities and varying beam velocities. These local alterations of the process parameters can cause an unwanted melting of the substrate material or a deterioration of the seam appearance. The results show that the substrate melting is primarily caused by low average interaction times between laser beam and brazing material. The melted area increases due to the existence of turning points in the oscillation pattern. The seam appearance can be improved by using higher frequencies, whereas turning points tend to cause rougher seam surfaces.

Keywords: Laser brazing; Keyhole brazing; Beam oscillation; Single-mode laser; Process efficiency

1. Introduction

Conventional laser brazing processes are based on the energy absorption by simple Fresnel absorption at the surface. By using highly reflective materials like aluminum or copper, this results in a low energy

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absorption rate and a low process efficiency. Another absorption mechanism is known from laser welding. By using a smaller spot size, the power density in the laser spot is increased, which leads to an evaporation of the material. In the resulting vapor capillary, the laser beam is absorbed multiple times, which significantly increases the process efficiency. Radel et al. (2016) showed the possibility of using a vapor capillary in a brazing process. This process is based on an overheating of the wire, whereby the additional energy is used to preheat the base material. In this way, it is possible to obtain smooth brazing seams without melting the base material.

Oscillations transversal to the brazing direction provide a distribution of the energy over a larger area (see Fig. 1), see Schultz et al. (2017). Oscillating the laser beam increases the velocity of the laser spot on the surface, which decreases the local interaction time of the process and changes the time-averaged power density. The interaction time is one variable of the power density that Suder et al. (2012) describes as one important factor influencing the penetration depth. Oscillations of the laser beam can thus adjust the penetration depth by adjusting the time-averaged power density. Fig. 1 shows an example of a distribution of the time-averaged power density resulting from a linear transversal oscillation of a laser beam from an investigation by Schultz et al. (2017). The linear oscillation has turning points at the end of the line; thus, the velocity of the beam varies along the movement. This leads to varying time-averaged power densities with two areas with higher values at the edges. Since the power density influences the penetration depth, this results in varying penetration depths. In the case of laser brazing, varying penetration depths can cause an unwanted melting of the substrate.

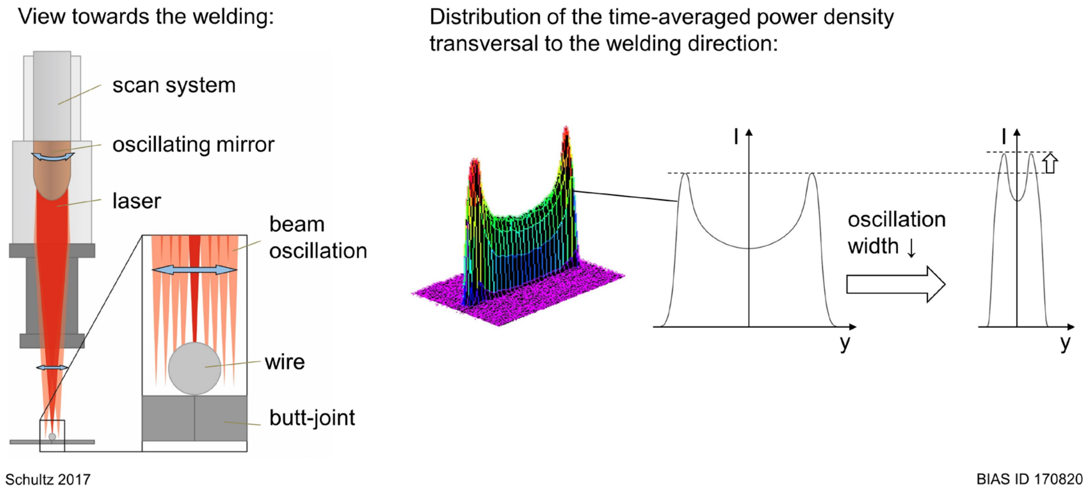

Fig. 1. Influence of a transversal linear laser beam oscillation on the time-averaged power density in laser welding; see Schultz et al. (2017).

Oscillations can also influence the seam quality. Heitmanek (2014) showed that oscillations of the laser beam above 40 Hz improve the seam quality. Also, Wang et al. (2016) observed the same for laser welding. Especially circular oscillations of the laser beam improve the weld surface morphology due to the rotating melt flow. When using a transversal linear oscillation strategy, the melt flow is obstructed by the wall of the molten pool, which leads to rougher welds. Smooth surfaces are important for brazing processes because they are often used to join parts that lie in the field of view. Heitmanek (2017) also showed that the velocity influences the seam appearance. Too high or too low velocities result in a lower seam quality because of the increased process dynamic, which causes the wetting behavior to deteriorate and therefore affects the quality of the seam edge. Turning points lead to different beam velocities across the surface; thus, the process dynamic can be influenced by the existence of turning points, leading to a deterioration of the seam appearance.

In this investigation, the influence of the different oscillation parameters and the existence of turning points in the context of the melting of the substrate material is examined. Additionally, the influence on the seam appearance, especially regarding to roughness and the seam edge, is investigated. It shall also be examined whether the presence of turning points has a negative impact. For this purpose, the approach of using the deep penetration process in combination with a linear beam oscillation for laser brazing of highly reflective materials is extended through the additional use of circularly beam oscillations. The circular oscillation strategy has no turning points and therefore provides a constant beam velocity. The special eight-shaped oscillation strategy also has a rotating beam movement and therefore melt flow, while there are turning points in the middle.

2. Experimental

The experiments were carried out using an IPG YLR100SM single-mode fiber laser with a nominal focal diameter of 15 µm and a maximum power of 1 kW. The oscillation of the laser beam was realized by a two-dimensional SCANLAB welDYNA beam scanning system. The collimation length and the focal length were 200 mm, leading to a nominal spot diameter of 15 µm at the wire surface. The three different oscillation strategies are illustrated in Fig. 2.

For the bead-on-plate samples, zinc-coated steel (DC 04 ZE 50/50) with a thickness of 0.7 mm and AlSi12 wire with a diameter of 1.2 mm were used. The metal sheets were cleaned with ethanol prior to brazing. The wire was applied in a leading configuration with an angle of 30° to the metal sheet surface. The focal spot was positioned on top of the wire surface. The process zone was protected using argon as a shielding gas. Fig. 3 displays the experimental setup.

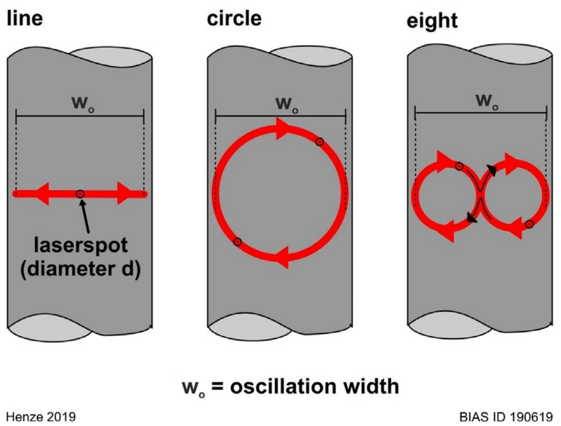

Fig. 2. The applied oscillation strategies: line (a), circle (b) and eight- shaped (c).

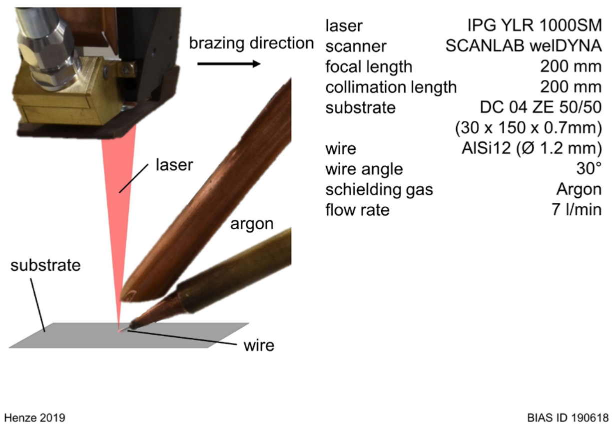

Fig. 3. The experimental setup.

The oscillation width was adjusted as described in Fig. 2. Table 1 shows the parameters of the laser brazing process. The oscillation width was adjusted based on the center of the laser spot. The oscillation strategy, frequency, and oscillation width were varied during the experiments.

Table 1. Laser brazing parameters.

Laser power	450 W
Brazing speed	1.0 m/min
Wire speed	1.87 m/min
Oscillation strategy	Line, circle, eight-shaped
Oscillation width	1.0 mm to 1.4 mm
Frequency	100 Hz to 300 Hz

To compare the different oscillation parameters, the average beam velocity $\overline{\mathrm{v}}$ of the beam oscillation was calculated with Equations (1) and (2) using the oscillation width $\mathrm{w_o}$ and the oscillation frequency f. For simplification, the wire movement, due to the comparatively small value of the wire speed, and the surface shape were not considered for the calculation. The average interaction time $\overline{\tau}_\mathrm{i}$ was calculated with Equation (3) according to Suder et al. (2012) by the spot diameter d and the average beam velocity.

Table 2 shows the calculated average interaction times for the tested parameters. The interaction time increased with decreasing frequency and oscillation width. The line and the eight-shaped oscillation strategies had turning points; thus, the velocity of the laser beam was not constant during the movement. The turning points of the line were at the edges of the wire, whereas the turning points of the special eight-shaped oscillation were in the middle. The calculated velocity and interaction time were average values.

$$\overline{\mathrm{v}}_{\mathrm{line}} = 2 \cdot \mathrm{w_o} \cdot \mathrm{f} \tag{1}$$

$$\overline{\mathrm{v}}_{\mathrm{circle}} = \overline{\mathrm{v}}_{\mathrm{eight}} = \pi \cdot \mathrm{w_o} \cdot \mathrm{f} \tag{2}$$

$$\overline{\tau}_\mathrm{i} = \frac{\mathrm{d}}{\overline{\mathrm{v}}_\mathrm{i}} \tag{3}$$

Table 2. Average interaction times for the different oscillation strategies, frequencies and oscillation widths.

strategy	frequency	oscillation width	beam velocity	interaction time
	Hz	mm	m/min	µs
line	100	1.2	14.40	62.5
	200	1.2	28.80	31.3
	300	1.2	43.20	20.8
circle	100	1.2	22.62	39.8
	200	1.0	37.70	23.9
	200	1.2	45.24	19.9
	200	1.4	52.78	17.1
	300	1.2	67.86	13.3
eight	100	1.2	22.62	39.8
	200	1.0	37.70	23.9
	200	1.2	45.24	19.9
	200	1.4	52.78	17.1
	300	1.2	67.86	13.3

The temperature of the melting pool during the process was measured with a DIAS PYROLINE HS 512N line pyrometer (spectral range 0.8 µm to 1.1 µm). The measuring line was positioned at the middle of the oscillation patterns and oriented transversal to the brazing direction. The pyrometer moved with the process. The emissivity was adjusted at 0.3. For each temperature value, 10 random rotations of the measured sample were measured, and the average value and standard deviation were calculated. The results are illustrated as a quotient of each value related to the measured average maximum temperature of the linear oscillation with 100 Hz and 1.2 mm.

The surface of the seam was evaluated using a confocal laser scanning microscope (KEYENCE VK-9700). The roughness was measured according to ISO 25178. The measurements were corrected with an s-filter of 2 µm and an l-filter of 1 mm.

The waviness of the seam edge was compared regarding to the wave width, as illustrated in Fig. 7. The wave width was measured as the distance from vale to vale. The values were measured manually based on images recorded with an incident light microscope. For each value, around 10 random waves on each side are measured, and the average value and standard deviation were calculated.

The presence of unwanted melting of the substrate was estimated using cross-sections. For each parameter set, three cross-sections were manufactured. The melted areas of the microsections were measured and the average values and standard deviations were calculated.

3. Results

Fig. 4 shows the temperature quotients for the maximum temperatures of the different oscillation strategies and frequencies. In the pyrometer measurement lines, the maximum temperatures for the linear and circular oscillations occurred at the melting pool edge, whereas the maximum temperature of the eight-shaped oscillation strategy was measured in the middle of the melting pool. The maximum temperatures decreased with increasing frequency. The highest temperature was measured for the linear and eight-shaped oscillation strategies. The temperature decreases with increasing width.

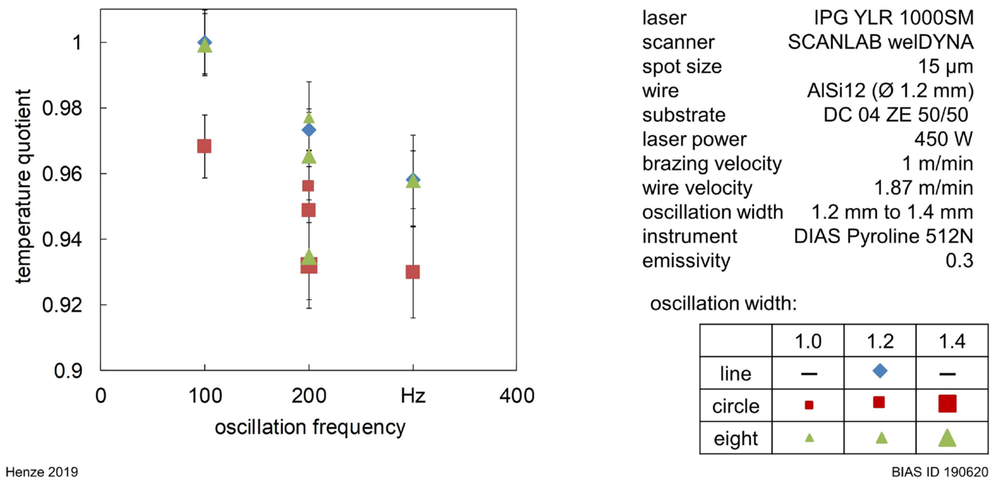

Fig. 4. Quotient of the measured maximum temperatures based on the value for the linear oscillation strategy at 100 Hz and 1.2 mm.

The microsections show a melting of the base material in some samples. Fig. 5 shows the melted area in the substrate as a function of the oscillation frequency and the oscillation width. The melted areas in the samples brazed with the linear and eight-shaped oscillation strategies are higher than for the circular oscillation strategy. The linear oscillation strategy has the highest values.

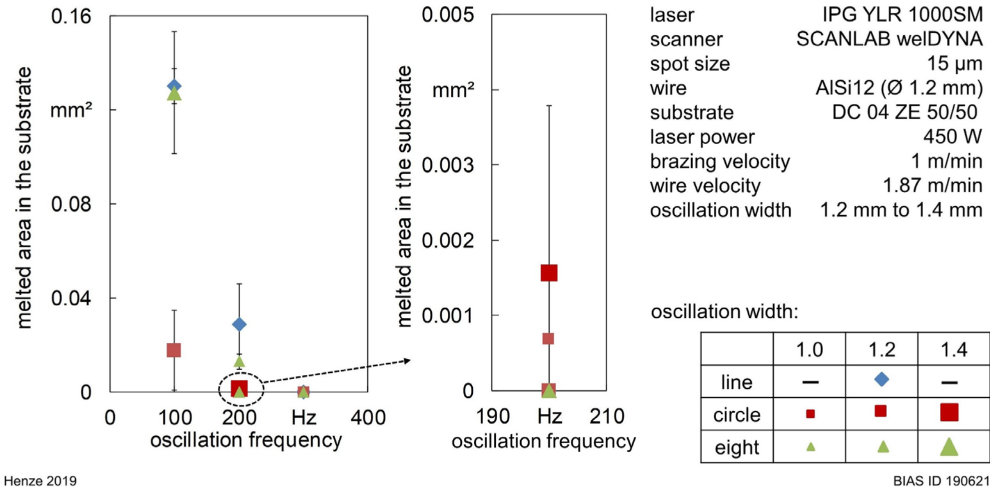

Fig. 5. Melted area as a function of the oscillation frequency.

Fig. 6 shows the resulting brazing seams for the different oscillation strategies. The seam edge of the samples has a wavelike structure. No edge notches occur. Fig. 7 shows the width of the seam edge waves as a function of the oscillation strategy, frequency and oscillation width. The width of the waves tends to increase with decreasing frequency. Also, the standard deviation of the values increases with decreasing frequency. A significant influence of the oscillation strategy is not recognizable.

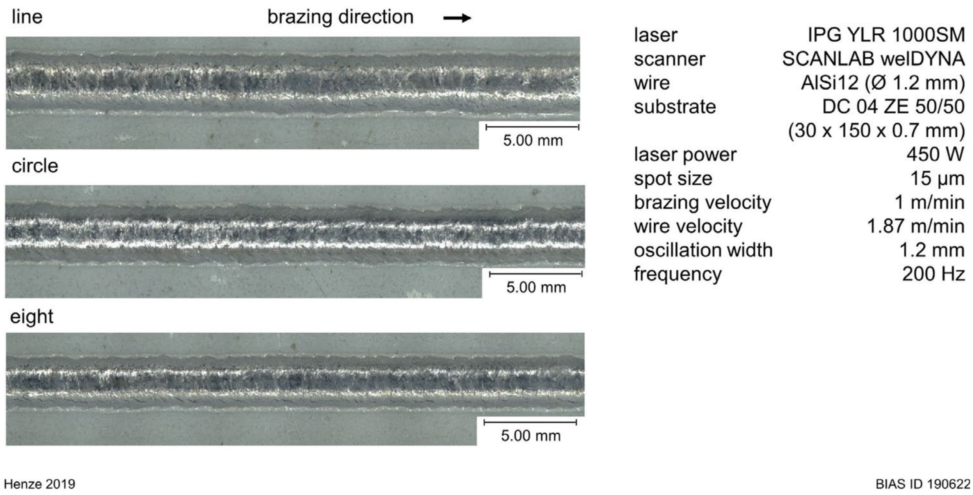

Fig. 6. Top view of samples brazed with different oscillation strategies (f= 200 Hz, w= 1.2 mm)

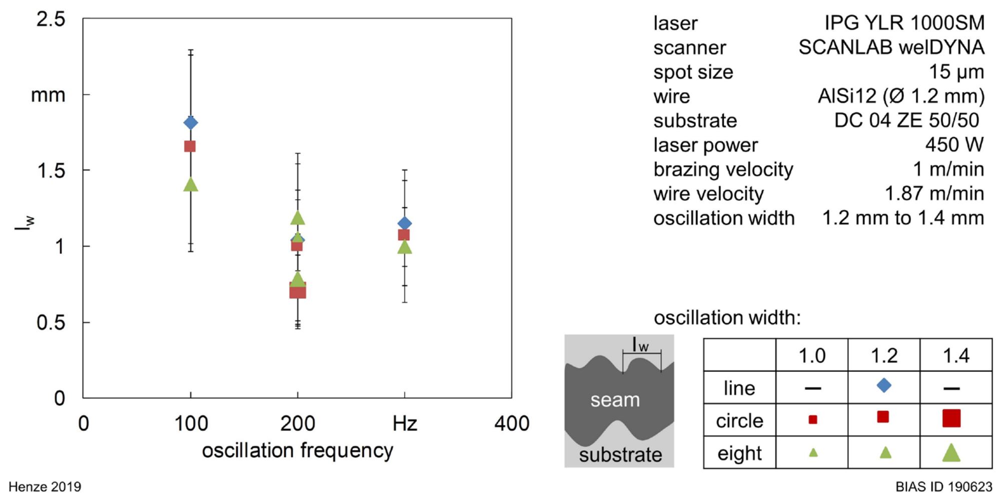

Fig. 7. Wave width of the seam edge l_w as a function of the frequency.

In addition to the seam waviness at the edge, the roughness Sa (arithmetical mean height) at the top of the seams is also measured. The results are illustrated in Fig. 8 as a function of the oscillation frequency and width. The roughness of the circular oscillation strategy has the smallest values. The linear oscillation strategy has the highest roughness.

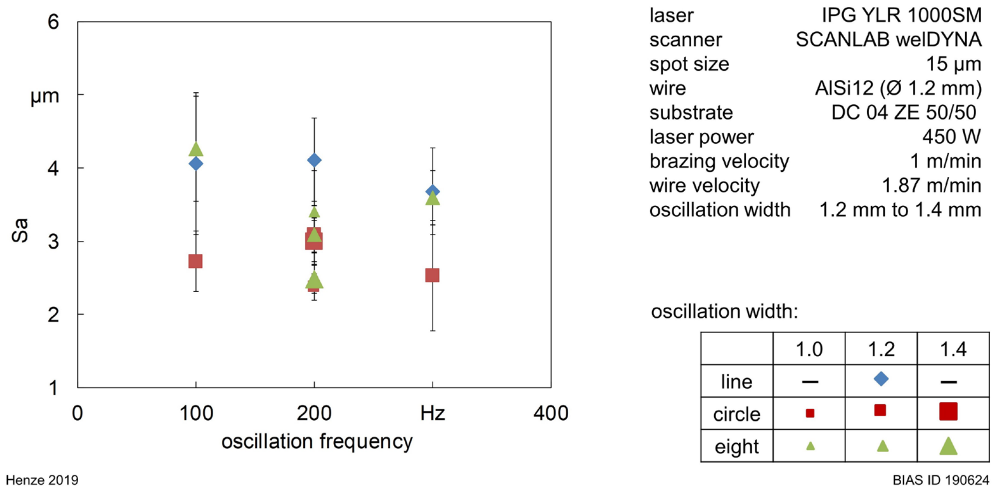

Fig. 8. Roughness Sa of the samples as a function of the oscillation frequency.

4. Discussion

Laser brazing with keyhole formation and beam oscillation is also possible with the use of different oscillation strategies. The oscillation parameters have different influences on the process, the seam appearance and the seam quality.

Adjusting the oscillation parameters changes the actual velocity of the laser beam. The frequency defines the time needed for one rotation. For a longer trajectory length, the velocity must be higher to complete one rotation at the same time as for shorter trajectory lengths. For a first overview, the velocity of the beam can be calculated as an average value independent of velocity changes. The linear oscillation has a smaller trajectory length, which results in smaller average velocities. By adjusting the velocity, the interaction time between laser and material can also be adjusted. Thus, the oscillation parameters influence the maximum measured temperature in the melting pool. Fig. 9 shows the temperature quotient as a function of the average beam velocity to illustrate this correlation. Increasing actual velocities results in decreasing temperatures due to the decreased interaction time. The linear and special eight-shaped oscillation strategies have higher temperatures than the circular oscillation strategy because of the turning points in the movement. At these points, the beam slows down to the wire speed for a short time, which increases the interaction time and therefore the time-averaged power density. For the linear oscillation strategy, the turning points are at the edges of the seam, whereas the turning point of the eight-shaped oscillation strategy is in the middle. Therefore, the highest temperature for the linear strategy is at the edge. and for the eight-shaped strategy it is in the middle. Because of the high frequencies, the individual circles of the circular oscillation strategy overlap near the edges, resulting in maximum temperatures at the edges for the circular oscillation strategy.

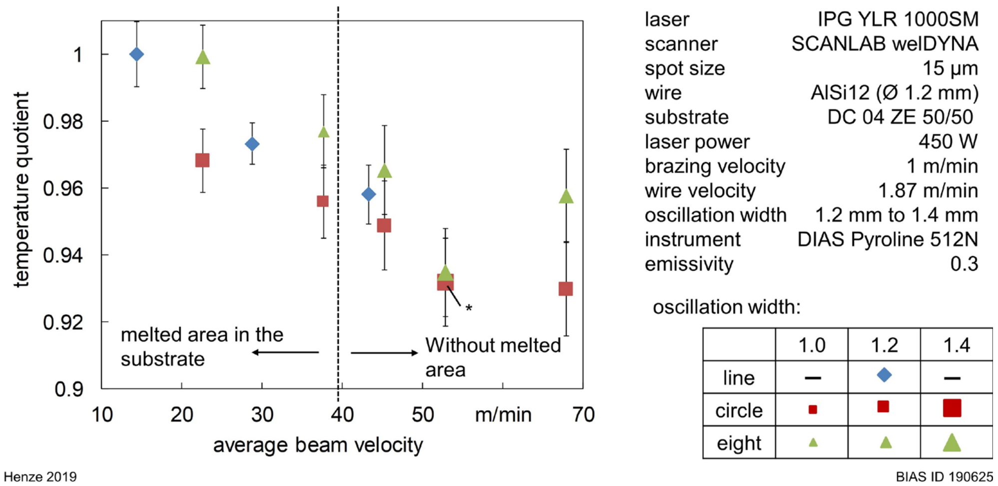

Fig. 9. Maximum temperature as a function of the average laser beam velocity. The dotted line marks the threshold where a melting of the substrate occurred (*: Single value with melted area in substrate right of dotted line).

In laser brazing with keyhole formation, the penetration depth resulting from the keyhole depth is an important factor. The penetration depth must be high enough for a complete melting of the brazing material but low enough to prevent an unwanted melting of the base material. The interaction time between laser and material depending on the actual velocity of the laser beam is a factor which influences the penetration depth. Some samples show melted areas in the substrate material. According to Fig. 9, these oscillation parameters had the smallest average beam velocities. The average interaction times of these samples were therefore higher, which results in higher maximum temperatures in the melt pool. The velocity of the beam was too low to prevent a melting of the base material. The dotted line in Fig. 9 shows the transition from samples with melted substrate material (left side) to samples without a melting of the base material (right side). Apart from one small melted area in the sample with circular oscillation at a frequency of 200 Hz and an oscillation width of 1.4 mm, none of the samples to the right of the line had melted areas in the base material. None of the microsections of the samples with turning points to the right of the dotted line showed melted areas in the substrate material. However, the maximum measured temperature tended to be higher than for the circular oscillation strategy without turning points. Turning points thus result in higher temperatures but do not automatically lead to melted substrate material. In the case of samples brazed with lower velocities, the turning points enlarge the melted area. A melting of the substrate seems to be mainly influenced by the average beam velocity, and thus the average interaction time, and not by higher local interaction times induced, for example, by turning points in the movement.

The seam appearance was evaluated regarding the waviness of the seam edge and the roughness at the top of the seam. The seam appearance is another important factor in brazing processes because these are often used in the field of view, resulting in the need for a good seam appearance. Increasing the frequency has a positive influence on the smoothness of the seam edge because the standard deviation of the wave width decreases, as does the wave width. The oscillation strategy and thus the varying beam velocities have no significant influence on the waviness of the seam edge. Also, the roughness on top of the seam tends to decrease with increasing frequency. The linear oscillation strategy has higher roughness for all frequencies resulting probably from the disturbance of the melt flow by the walls, as described by Wang et. al. (2016). The melt flows against already solidified parts which causes accumulations and direction changings. This decreases the stability of the melt flow and results in rougher weld surfaces. The circular oscillation strategy has instead smaller values resulting probably from the rotating melt flow. The eight-shaped oscillation strategy shows changing behaviour in the case of different frequencies.

5. Conclusion

The following conclusions can be drawn based on the study:

- Substrate melting in keyhole brazing is primarily caused by low average interaction times between laser beam and brazing material.
- The melted area in the substrate material increases due to the existence of turning points in the oscillation pattern. In comparison, the circle oscillation pattern without turning points showed smaller melted areas.
- The seam appearance can be improved by using higher frequencies. The seam edge becomes smoother and the roughness on top of the seam decreases. Turning points tend to cause rougher seam surfaces.

Acknowledgements

Funding by the DFG is gratefully acknowledged (DFG - Deutsche Forschungsgemeinschaft, engl. German Research Foundation, project number: 326408602).

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