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Impact on accessibility, heat distortion and process reliability of planned process interruptions in laser beam brazing processes

Arend Janssen[1], Marcel Stamm[1], Lars Spangemacher[2], Hauke Buse[2], Thomas Schüning[1*]

[1] University of Applied Science Emden-Leer, Emden, Germany; arendjanssen86@gmail.com (AJ); marcel.stamm@hs-emden-leer.de (MS)
[2] thyssenkrupp Marine Systems, Emden, Germany; lars.spangemacher@thyssenkrupp.com (LS); hauke.buse@thyssenkrupp.com (HB)
*Correspondence: thomas.schuening@hs-emden-leer.de

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Abstract
The objective to increase the transferred power ("heat") of heat exchangers, here finned heat exchangers, leads to an increase in the heat transfer surfaces through thinner wall thicknesses and thus higher packing densities. This transfer can be further optimized by choosing materials with high heat transfer coefficients like copper. Various joining processes, such as welding or brazing can be used to complete the heat exchanger components. Laser beam brazing has an outstanding advantage: heat is applied only where it is needed to create bonds. The base material does not melt and the heat-affected zone becomes smaller, reducing the risk of mechanical distortion. Laser beam brazing has a disadvantage in terms of accessibility. In dense situations, the laser beam may fail to reach its target because the brazed joints may be hidden. Such "shadowing" means that the process cannot be carried out in ideal conditions, i.e., in the case of a circumferential seam, a full, uninterrupted circular movement may not be possible at an angle of incidence of 45 degrees. If steeper or flatter angles are chosen to achieve accessibility, this will result in uneven heating of the parts being joined, in this case the fin and the tube. The work presented shows the development of such brazing process. Firstly, it has to be established whether interruption and resumption of the laser brazing process will produce a usable result and further studies on heat distortion and process stability will be carried out to ensure the process is suitable for batch production.

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1. Introduction

Heat exchangers, more precisely finned heat exchangers (FHE), an example of such is shown in Fig. 1, are commonly designed with a batch of flat sheets, the so-called fins. These fins are connected to tubes, in general they are joined together at a 90° angle. One medium flows inside the tubes, while the other medium flows or rests outside the tubes. The surfaces of the fins and tubes absorb the heat from one medium and transfer it to the other. Obviously, larger surfaces ensure higher performance of the device. Thus, an increasing number of fins increases the performance. The design of a more compact FHE is achieved by using thinner fin plates, smaller tube diameters, and an optimized package design of tubes and fins. In addition, the material selected for the FHE components affects the performance of the device. With a high specific heat capacity of 385 $J \cdot kg^{-1} \cdot K^{-1}$ (Binder, 1999), copper grants good heat transmission, it is also robust to chemical corrosion.

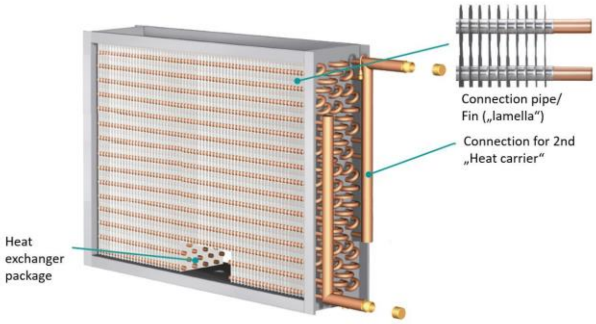

Fig. 1. Example of finned heat exchanger with tubes made from copper (Polar Kaeltetechnik 2024)

Copper components can be joined by a variety of methods including welding, brazing, press-fitting, etc. Brazing is a joining process in which two or more metal work pieces are joined by a molten filler metal (Groover, 2007) exceeding temperatures of 450°C (Jacobson , 2005; Brandner, 2003) The filler metal, which has a lower melting point than the metals being joined, flows into the gap (between the parts) and fills it. The Fig. 2 below shows the principle of a laser brazing process at an overlap joint:

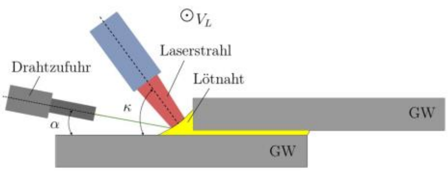

Fig. 2. Principle of laser beam brazing

Hence, brazing does not melt the work pieces, differentiating it from welding. The main purpose of the device is to transfer heat, so the mechanical stability of the FHE can therefore be considered secondary. In this case, brazing is chosen because of the need for high fin packing density and low thermal distortion. The optimization of the design of heat exchangers was and is part of many works. The work of Kunpeng Guo (Guo 2015) should be mentioned here: Particularly Chapter 3 offers a comprehensive overview about the design optimization of multi stream plate fin heat exchangers. In the present application, however, the design of the finned heat exchanger depends on the recipient in which it is installed. Consequently, it was a design to external requirements.

Laser brazing - influence of flow heat

Brazing in general (including laser brazing) requires the braze wire to be completely melted in order to wet the materials to be joined, although remaining the temperature below the melting temperature of the joining partners (Jacobson 2005): The laser beam is used to heat the joining partners and melt the braze material. Within the "joining-zone", the laser spot should be significantly larger than the diameter of the braze wire so that the braze material can be distributed evenly across the joining partners to create a large bonding surface.

The larger spot diameter also ensures, that the joining partners are heated at the side of the braze material and in advance of its trajectory by the laser. A large proportion of the laser beam is used to heat the braze wire. The underlying surface is less directly heated by the laser. Here, the joint itself is also heated by heat conduction in the joining partner.

In case of the challenging accessibility of braze joints of the tube-plate connection used here, the laser cannot reach the end of the process directly. Due to the diameter of the laser, however, sufficient energy can be introduced, so that the braze material can be re-melted at the start of the process by heat conduction and the areas are sufficiently heated, thereby achieving a homogeneous connection between the end of the process and the start of the process in the case of rotationally symmetrical components.

The re-melting of the braze material is also favored by the high thermal conductivity of the copper material used and by power control of the laser at the end of the brazing process. It has been shown experimentally that complete coverage with the laser beam is not necessary to achieve a secure connection. Fig. 3 to 5 shall illustrate this process:

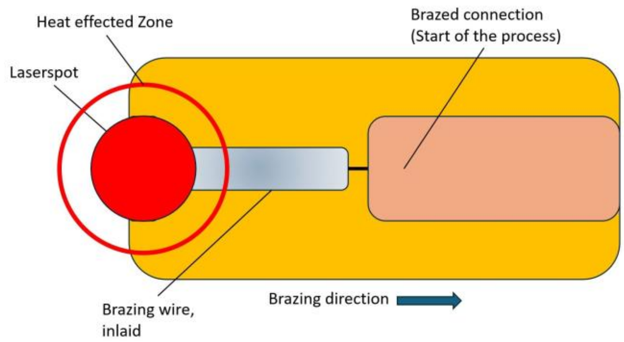

Fig. 3. Within the laser brazing process

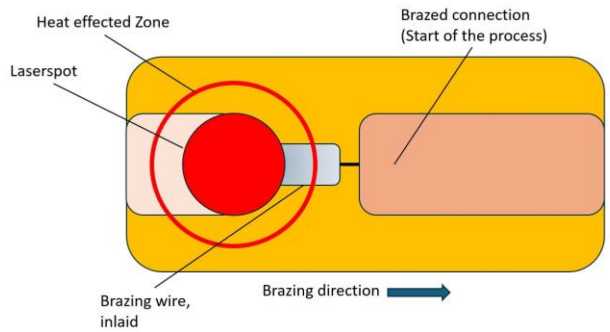

Fig. 4. Shortly before the end of the laser brazing process

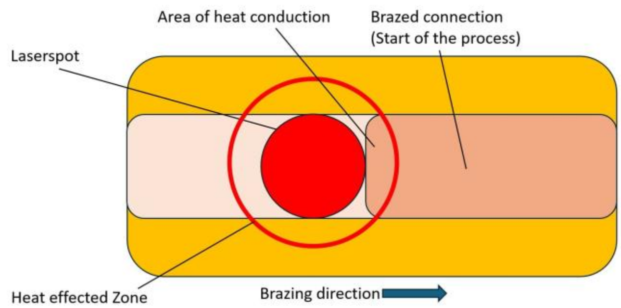

Fig. 5. End of the process with heat conduction to the beginning of the process

2. Aims

Due to the high intensity, the energy required to heat up the base material to be brazed and melt the braze material can be applied in a much targeted location. There is also a clear geometry limit in which energy is applied. This is a major advantage over other brazing processes, such as inductive brazing. The formation of brittle intermetallic phases is reduced due to the short exposure times of the laser, via which the energy input into the work piece is realised (Hanebuth 1996). In narrow, small areas, the deformation of individual parts during the joining process is reduced and the overall quality of the end product is improved. A key factor in the laser brazing process is the choice of an optics combination that is precisely optimised for the conditions of the process. This selection influences the beam´s caustic which in turn plays a significant role in the outcome of the process. The optic is mounted on a robot, so the laser beam can be moved very precisely to the brazing points. The laser beam brazing process is selected as it matches the FHE requirements best. Manufacturing aspects are also evaluated reasonable, automated assembly lines with industrial robots are characterized by accuracy and repeatability once the process is established. General pre-treatment and post-treatment are also not indicated, high productivity results from the project framework. However, process development has to cope with a disadvantage of laser brazing, which is caused by the high packing density required to achieve the desired heat transfer. The area of interest, where the laser spot joins the materials, may be obscured by other parts of the FHE (tubes and fins), making it inaccessible for the ideal process. Figure 6 shows a schematic illustration of such a situation in which there is no all-round accessibility for the laser beam to the joint due to structural conditions.

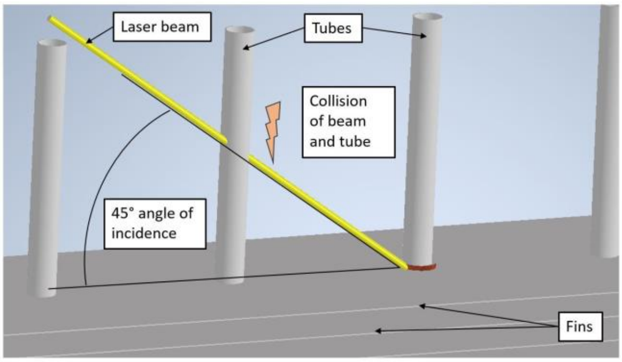

Fig. 6. Scenario showing need for "2-step" brazing process due to insufficient accessibility of the laser beam to the joint

Such a process is defined by a circumferential T-joint between the tube and fin: the robot-mounted laser optic performs an uninterrupted circular motion, ensuring a 45° angle of incidence (κ) between the fin and tube. In summary, the required package density may impede either an ideal angle of incidence or an uninterrupted motion. On the other hand, achieving accessibility by using steeper or flatter angles of incidence will result in uneven heat distribution and therefore poor-quality joints. The aim of this work is to prove the brazing capability by investigating a planned interruption and resumption of the laser process to maintain the ideal angle of incidence and the associated process stability. In the first step the general feasibility of stopping and restarting of the laser beam brazing process is verified. In the second step, it is analyzed if full brazed seams can be produced with complete process interruptions when a geometric obstacle to the beam occurs. The overall thermal effect should benefit from this step-by-step approach. Subsequent studies of heat distortion and related process stability should ensure brazeability. Once challenging design aspects have been mastered and brazing capability has been demonstrated, the process is qualified for volume production of custom (special design) copper fin heat exchangers under production conditions. Automated laser assembly cells achieve high levels of productivity and are therefore able to produce even special batch sizes economically.

3. Former and preparation work

In preliminary studies the copper made fins and tubes have shown good results using the brazing alloy AH SiKuP 5/ CuP 281; it is an easy-flowing, low-melting, phosphorus-containing brazing alloy for operating temperatures from -50°C to 150° C. It is designed for brazing copper and copper alloys with a working temperature of 710°C, the joints can be carried out without flux due to the phosphorus (Datasheet Armin Hain GmbH, 2024).

As the selected brazing material is flux-free, the necessity for both pre- and post-processing is reduced. Due to its silver content of only 5%, the thermal conductivity remains virtually unaffected. Silver with k=407 $W \cdot m^{-1} \cdot K^{-1}$ has a similar thermal conductivity to copper with k=395 $W \cdot m^{-1} \cdot K^{-1}$ (Fischer, 2005), and the resistance to corrosion is also positively influenced. The favorable physical properties of the chosen base material, particularly the very high thermal conductivity, are also retained at the joints.

Either feeding the braze with wire or using preformed braze rings (shown in Fig.7) could be applied in serial manufacturing, but a prefabricated braze ring is confirmed as the more successfully appropriated method, the quality of the joint has a better concave shape and better gap filling, a higher level of process stability is assumed.

Braze ring 12x1mm
(diameter x wall thickness)

Fig. 7. Showing preformed ring made of brazing material

Other previous studies (Maul 2023) have determined the brazing gap by comparing the results of different diameters of the fin´s bore. Gaps larger than 0.2 mm have the advantage of larger positive substance joint, even the rear side is loaded with braze. However, unfavorable diameter combinations may result in imperfections in the joints, as the tubes are not completely surrounded by braze. The brazing gap is defined at 0.1 mm with a limit of 0.2 mm (Maul 2023), which allows stable production. The next influencing factor is the tool. In this scientific work the LDF 4000 / 2400 Hybrid laser system from the company Laserline GmbH, Germany is used to braze a section of an FHE. The diode laser consists of five diode stacks, which in turn consist of several diode laser bars with different wavelength (940 nm, 960 nm, 980 nm) and corresponding cooling. The decoupled laser beam is then guided into the OTS-5 processing head via the optical fiber. In the processing head, the beam is first collimated by a lens and then focused by the focusing optics to form a laser spot on the work pieces surface. When leaving the lens, the focused beam forms a waist shaped curve which can be approximately described as a Gaussian beam (see Fig. 8 for geometric parameters). The outer line is called the caustic.

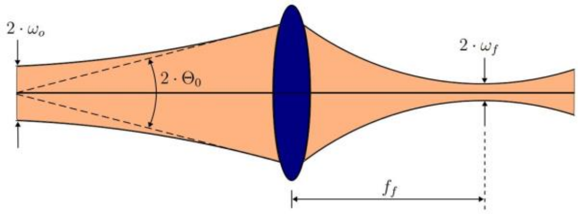

Fig. 8. Caustic of the laser beam (Pedrotti, 2005)

The beam caustic is significantly influenced by the combination of optics. When selecting a suitable processing lens, it has to be ensured that the spot diameter is larger than the braze wire diameter in order to heat the base material sufficiently for uniform wetting. Another criterion is the geometric conditions already mentioned, which are defined by the assembly. These include the working distance between the optical components and the pre-positioned joining partner (see Fig. 6) as well as unobstructed access of the laser beam. This is favoured by a large focus spot, as the laser beam runs more parallel.

A processing lens with a focal length of 730 mm is selected for this specific process, as this provides a suitable compromise between the criteria listed.

Lambda (λ) is the wavelength of the emitted light, which is related to source of light, in this case the diodes provide an averaged value of 960 nm (Bliedtner et al., 2013) and a beam quality of 0.00694 (K). The diameter of the beam ($2\omega_f$), the spot size, can be calculated by solving the following equation, delivering a spot size diameter of 2.78 mm.

$$2\omega_f \approx f_f \cdot 2\theta_0 = f_f \cdot \frac{2\lambda}{\pi \cdot \omega_0} \tag{1}$$

To determine the beam diameter at a given distance (z) from the lens, such as a near tube, the following equation must be solved (Neumann, 2021):

$$\omega(z) = \omega_f \sqrt{1 + \left(z \frac{\lambda}{K \cdot \pi \cdot \omega_f^2}\right)^2} \tag{2}$$

4. Experimental implementation

A KUKA KR 30-3 industrial robot is used, which is controlled by the KRC4 controller. The robot's six axes, an additional 2- axis positioner with a jaw chuck (see Fig. 9 left), and the laser system are also controlled by the KRC4 controller. In these experiments, the robot's axis is adjusted to position the optics at the required angle of incidence of 45° and the laser beam is aimed directly at the brazing gap. The copper sheets are held by magnets (see Fig. 9 right) on a spacer ring and the three jaws to prevent unwanted rotation. Due to the special geometric requirements and the limited space, it is better to use a preformed ring of brazing wire.

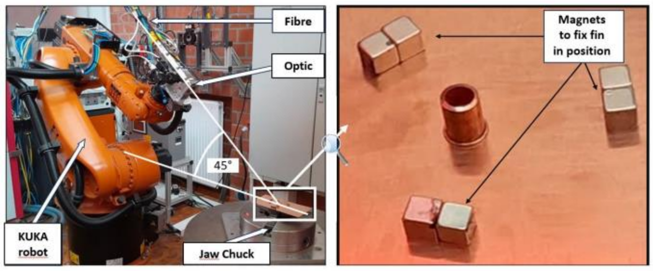

Fig. 9. Laser brazing assembly cell, consisting of laser optic, fiber cable, robot, 2-axis positioner and sample in place (detail)

With regard to the planned batch process, the deposition of the brazing material is carried out manually. This ensures fixation and deposition of the material on the spot without any further "shadowing". If the brazing material is to be deposited by wire feed, instead, the dimensions of the feed unit must also be considered in the accessibility study. When considering the reliability of brazing for the planned serial manufacturing process, the angle of incidence becomes crucial. Despite the acceptable results with angles up to 10° under laboratory conditions, the importance cannot be underestimated. As mentioned above, steeper or flatter angles to gain access will result in uneven heat distribution between the tubes and fins. Uneven heating is a known cause of failure modes such as local melting, uneven braze distribution, or erosion (Heitmanek, 2014).

Under serial manufacturing conditions these issues will enhance by deviations of single parts, the ability for serial production will be foiled. Therefore, the interrupted, ("2-step") brazing process needs to be put in practice and tested. Before putting the laser process into practice, possible access based on the FHE dimensions and the cell frame conditions must be considered to determine movements of the axis motion: the dimensions of the final structure of the FHE and its individual components set a base point for calculation of the accessibility, in this case the collision of the beam with adjacent tubes must be avoided. The design assumes parallel tubes with a distance of 83 mm from tube to tube. By considering the 45° angle of incidence, this distance also appears in the Z direction of the coordinate system. Thus, the final distance from the braze point to the next tube in line of the beam is 117.38 mm, calculated by the Pythagorean Theorem. Knowing this distance, the focal diameter of the beam at the intersection of the tube and the beam can be calculated. Constraining the beams caustic, this diameter is a variable value as it depends on the distance between the laser optic and the obstacle. The equation introduced (see equation (2)) gives the required value of 7.917 mm in diameter (2* ω(z)) for the beam width at the distance of 117.38 mm:

$$2^*\omega(z)=7.917=1.39\sqrt{1+\left(117.38\frac{0.00096}{0.00694\cdot\pi\cdot1.39^2}\right)^2} \tag{3}$$

To avoid collisions due to tolerances, a 2 mm clearance on each side is also considered and the beam width is considered as 8 mm. It can be shown that a rotation of 163.43° on a circular path is possible without collision with the proximate tubes. On the other hand, 16.47° of the seams cannot be reached because the adjacent tube will interfere. Fig. 10 below shows these geometrical conditions.

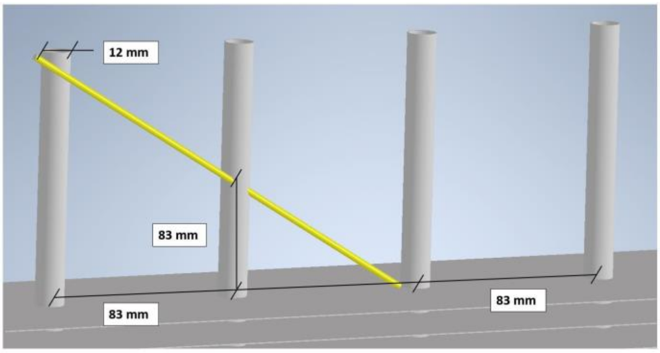

Fig. 10. Drawing showing the geometrical conditions of brazing accessibility

The spot size of the beam is the other base point for the calculation. The beam does not form a point, but a circular area, the spot size, where it impacts the brazing point. The beam spot size has a value of 2.78 mm.

Table 1. Calculation of max. accessibility (rotation) under 45° angle

Geometrical measure from beam rotation	Value [mm]	Percentage of tube circumference [%]	Degrees of tube circumference [°]
Circumference of half rotation	260.75	100.00	180.00
Obstacle – ½ tube	-12.00	-4.60	-8.28
Beam width at next tube	-8.00	-3.07	-5.52
Safety clearance	-4.00	-1.53	-2.76
Sum of rotation	236.75	90.80	163.43

Table 2. Calculation of max. accessibility with spot under 45° angle

Geometrical measure from spot size	Value [mm]	Percentage of tube circumference [%]	Degrees of tube Circumference [°]
Circumference of tube	37.70	100.00	180.00
Spot size	2.78	7.37	13.27
Sum of spot size and rotation		98.17	176.70

The mathematical description shows that the tube circumference is not completely "covered" by the laser beam, "only" 98% or 176° is exposed by a half rotation. It is assumed that the "missing" area is also filled with liquid braze due to heat conduction and capillary forces. Therefore, these experiments are designed to demonstrate full circumferential coverage with an optically and technically sufficient seam with a rotation of only 163° on each side, in this case brazing capability is generally given. See Fig.11 for a sketch showing this “2-step” brazing process and an actual photo of a brazed seam applying this process. If the CAD data of the FHE and the assembly line are known and loaded into a suitable simulation or CAD software, the mathematical calculation can be supplemented and improved. For further improvement, the brazing process is performed in counter-rotating movements on each side. Due to the high and in this case fast heat transfer capability of copper, the process heat is quickly dissipated. Therefore, the end point of the first joint has the highest heat at that time, while the start point has a lower temperature. Continuing the second joint at the first start point will affect the overall temperature peak of the entire process and should result in less mechanical distortion.

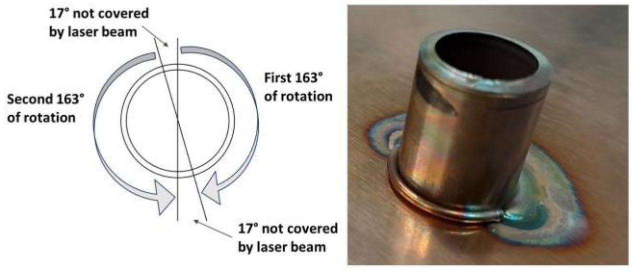

Fig. 11. Sketch of accessibility with a 45° angle of incidence, photo of seam after 163° rotation

5. Results and evaluation

Initial attempts were made with a 360° seam brazed in one step. The heat generated by this process caused severe distortion of the fins, including unwanted plastic yield. Process heat by reducing the energy input per unit length has already been minimized. Distortions usually cannot be avoided completely in thermal processes. The process heat always leads to shrinkage, residual stresses and often to considerable deformation (Schuler, 2019). To minimize distortion, the energy per length was reduced as much as possible. Gained experience shows that the process setting for quality joints with minimal heat is approximately 160 kJ/m at 990 W at 6.8 mm/s.

A heat input lower than described here may lead to faulty seams (see Fig. 12).

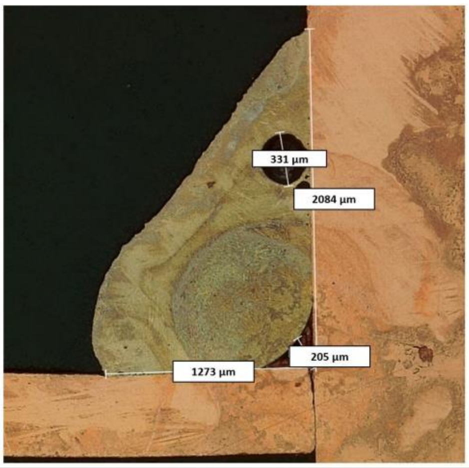

Fig. 12. Microsection of seam with under filling, convex shape and gas inclusion

Due to the insufficient heat the wetting capability and reduced viscosity leads to poor gap filling thus the braze forms no concave surface geometry over the entire circumference. Gas inclusion can also occur. These geometric deviations impede the heat flow as a result.

5.1. Brazed seam in one step (1 x 360°)

Previous tests have shown that the outer tube-fin connections can still be realized using 360° connections and that thermal distortion is manageable. The center joints, which have a greater distance between the tube and the outer edges of the fins, are more difficult. The ratio of sheet thickness to distance (area of heat input to the outer edge) determines the lever angle of the "warping force" and thus the resulting material distortion. This material distortion leads to a displacement of the joining zone relative to the laser spot and thus to incomplete melting of the filler material, which results in poor seam quality. The seams are almost plane to the sheet and do not form a convex joint. These obvious “optical” results are sufficient and do not require any further analysis. The approach will not lead to reasonable results. Fig. 13 below shows such a warped sheet metal.

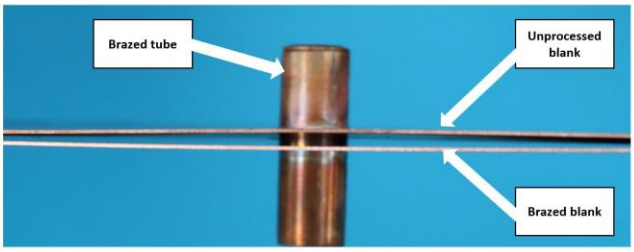

Fig. 13. Plastic yield up to 3.5 mm compared to original blank

5.2. Brazed seam in two steps (2 x 163°)

In these examples, the tube is encircled by the braze material, and the seam has a convex shape, which is expected for a “good” joint. No deviation is indicated, so the visual inspection shows no noticeable problems. During process development the process reliability, more specific, the material bonding of the joining partners, was evaluated using micrographs. For this subsequent metallographic examination, the samples are cut very close to both overlaps (Fig. 14), as this is the area of interest. Fig. 15 shows the complete re-melting and bonding of the braze material at the overlap. The brazing gap is completely filled on one side and half-filled on the other.

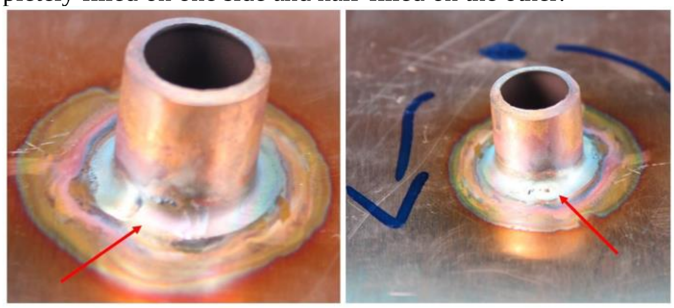

Fig. 14. Brazing seam overlap at start point (left) and interruption point (right)

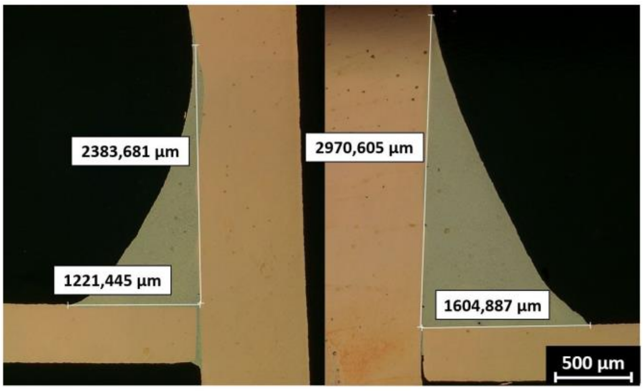

Fig. 15. Microsection near to first (left) and second (right) overlap corresponding to Fig. 14

Fig. 16 shows that the remaining mechanical distortion has a residual value of approximately 1 mm compared to an unprocessed sheet.

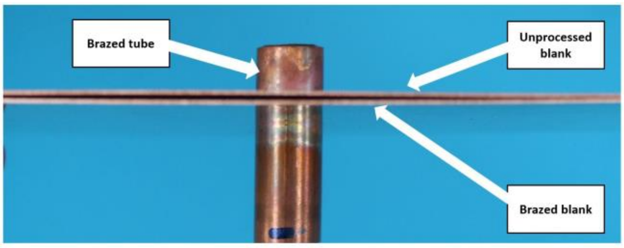

Fig. 16. Plastic yield up to 1 mm compared to original blank

Besides the positive effect on mechanical deformation, the heat affected zone is reduced from 36 mm to 28 mm in diameter compared to the brazing process in one step (see Fig.17).

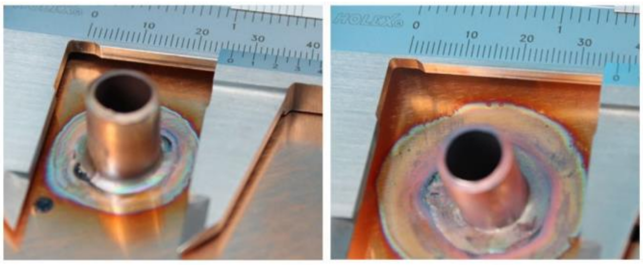

Fig. 17. Heat affected zone in comparison (1x360° left and 2x163° right)

In addition to this destructive testing, a procedure was established for quality assurance that uses heat flow thermography: Since irregularities occur inside or on the surface of the joints disturb the heat transfer between the joining partners, thermography can help to detect these irregularities of the heat flow by means of the infrared radiation emitted from the surface of the test specimen. (Prints 2021)

Therefore, one joining partner (here the pipe) was heated (by dipping it into hot water) and the heat flow into the other component (fin) was shown using infrared images (Camera: Optris PI450i). A uniform distribution of the heat transfer, which is represented by different colours, shows a geometrically uniform connection, thus a “good joint”. As an example of a “good joint”, Fig. 18 shows a closed seam: A round and symmetrical spread of the colour spectrum demonstrates an unimpaired heat transfer.

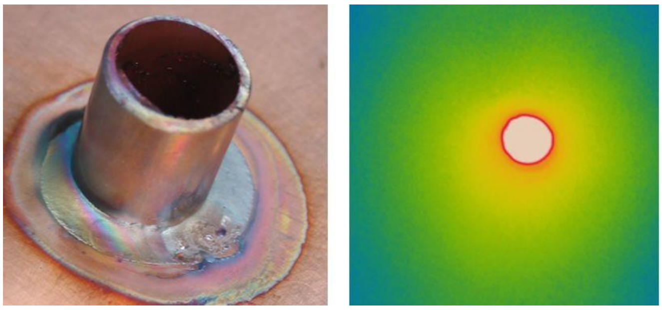

Fig 18. Picture showing a completely attached fin and the corresponding thermographic image

In contrast, Fig. 19 shows an excessive bonding to the pipe and an imperfect connected fin: The asymmetry of the colour spectrum indicates incomplete heat transfer between the joining partners.

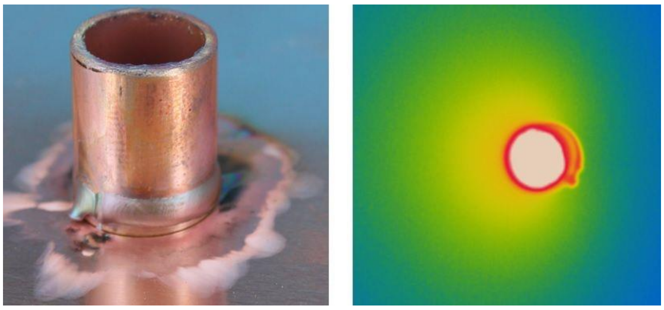

Fig 19. Picture showing an incomplete attached fin and the corresponding thermographic image

5.3. Discussion

From a manufacturing point of view, the design of the FHE was an absolute challenge. The originally planned single-step 360° brazing process can only be carried out at very steep angles. The uneven heat distribution, exacerbated by manufacturing tolerances, makes the process unreliable. The resulting failure costs would be many times higher with this solution ("rule of ten"). In addition, very strong deformation was observed. The basic brazeability according to DIN 8514 is questionable. Other solutions, such as grooves for reinforcement or greater material thicknesses, not only result in significantly higher material and manufacturing costs, they also contradict the design objectives. All of the solutions discussed also add costs, at least in their own way. The process developed here is therefore superior to the other solutions, and the original design can be reproduced. The process is much more robust and can be controlled while maintaining the ideal angle of incidence, resulting in low failure costs. The basic brazeability according to DIN 8514 is given. The only "disadvantage" is the longer cycle time due to the one-time rotation back to the starting point. However, this is negligible in the context of the entire production process, including the insertion of solder rings, fins, etc. Nevertheless, a clamping system should be used to further reduce distortion. Fins and tubes have different material thicknesses and geometries and therefore different masses. Even with an incidence angle of 45° and a precisely aimed laser beam, this can lead to imperfections due to different heat absorption and temperatures of the joining parts. To improve the quality even more, further optimization is subject of future investigations.

6. Summary and conclusion

This work has successfully demonstrated that laser beam brazing is a suitable manufacturing method for applying thin fins to tubes. This knowledge is essential for the further course of the project, the fabrication of complete heat exchanger packages. Important parameter sets have been developed and the assumption that the capillary forces of the brazing process can produce a complete joint, even when the process is interrupted, has been confirmed. This makes it possible to produce brazed joints that are difficult to access. Specifically, it was shown that it is possible to divide the circumferential seam into two brazing steps/seams and achieve the same good joint quality as a circumferential seam. This process adaptation allows for tight geometries and avoids collisions between the laser and the work piece, which may add costs due to increased cycle times, but does not impose design constraints.

At the same time, it has been shown that clamping the work piece is essential to reduce the thermal distortion. This thermal distortion cannot be completely avoided due to the geometry: the area of the fins in relation to the thickness of the fins provides a very large lever arm to bend when exposed to heat. In summary, the design can be maintained. Alternative methods to reduce the thermal distortion such as:

- Increase material thickness: Contradicts the design, adds weight and material costs,
- Stiffening beads: Contradicts the design, adds costs due to additional process step,

can be discarded because they would result in additional costs or a major redesign. Clamping technology will therefore be an important optimization step in the future.

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