Lasers in Manufacturing Conference 2017

Micro laser joining of capillary tubes for medical applications using filler metal

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Abstract

There is a continuously increasing demand for laser beam welding processes in the field of medical devices. Due to complex component geometry, weld seam contour, the shape of the weld seam and tolerance requirements, the use of filler metal is unavoidable under certain circumstances. Established autogenous laser beam welding technology may lead to a significant reduction of wall thickness and is therefore unsuitable for welding complex and thin-walled capillary tubes with wall thicknesses of less than 200 µm.
The present paper introduces a novel technique to address the particular joining geometry of these structures in order to avoid weld seam irregularities. The process requires bridging the air gap during welding and has been implemented using an automated wire feed drive, capable of feeding wire diameters between 300 and 600 µm.
Focusing on joining stainless steel capillary tubes (1.4301) with filler metal, metallographic cross sections and tensile tests were used to evaluate the effect of joining process parameters (e.g. laser spot size, pulse frequency, feeder speed etc.) on joint properties. Preliminary results were used to establish a process parameter envelope resulting in good and reproducible joint properties.
Results allow an outlook towards a generalization of the above process parameters, taking into account the special requirements of joining bent capillary tubes.

Keywords: Micro Processing; Micro-Joining (Welding and Brazing); capillary tubes; medical devices

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1. Introduction

Laser welding is an innovative method of material and fabric processing, and is extensively applied in the field of medical technology due to its design freedom, the contact- and force-free operation, and the possibility of precisely controlling the energy input into the component [1]. Due to the high precision of the process, it is possible to minimize or completely eliminate subsequent steps in the manufacturing process [2]. The aim of this work is to develop parameter fields for laser beam welding of medical components with filler metal and to examine and evaluate the joint properties compared to welds without filler metal. Starting from joints with a straight weld seam, the laser welding process will be further developed for the application with curved joint courses. The focus of the work lies on the economical processing of long rotationally and non-rotationally symmetric components (diameter: 0.5 - 5 mm, length: 30 - 50 mm) in combination with short rotationally symmetric parts with lengths up to 15 mm and a diameter range up to 5 mm.

2. Materials and methods

The experiments were conducted on stainless steel capillary tubes (1.4301) using a lamp-pumped pulsed Nd: YAG solid state laser (λ = 1064 nm) with a maximum average power of 120 W, a maximum pulse energy of 80 J and a maximum pulse output of 10 kW. This system has been augmented by an automated wire feed drive to deliver the filler material. The configuration is shown in Figure 1.

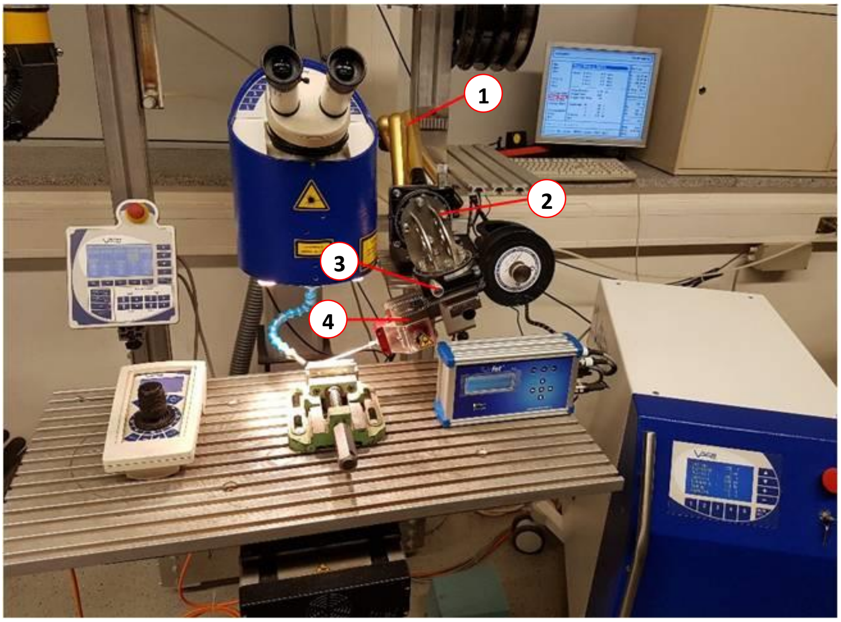

Fig. 1. Experimental setup with automated wire feeder. (1) Clamping arms; (2) pivot axis; (3) precision positioning system; (4) wire feeder

The wire feeder used here is suitable for diameters of less than 500 µm and has been chosen for its compact design, as well as its easy and cost efficient integration into the laser welding system via an open user interface.

For the approximate positioning of the wire to the joining point, the system has two flexible clamping arms, for fixing it to the laser system (see Fig. 1). A precision positioning system is used to align the wire tip with the designated weld seam. In order to adjust the angle of incidence of the wire with the axis of the laser beam, additional pivot axes were integrated into the system. As filler metal, QUALAS QL Med 4430 / 1.4430 with a diameter of 300 µm was used. A reduction of slip in the feed is achieved by form-fitting the helical-toothed drive rollers to the welding wire. For the exact positioning and feeding of the filler material, differently dimensioned capillaries and nozzles adapted to the wire diameter are used. The optimum leading feed angle was 25°, related to the workpiece surface

The programmable wire feed system can be adjusted to speeds between 0.1 and 150 mm/s. The spot size of the Nd: YAG solid-state laser system can be varied between 250 µm and 2.0 mm at increments of 50 µm using a beam telescope installed within the beam source. This makes it possible to change the focus diameter on the components surface at a constant working distance of 190 mm.

The capillary tubes were welded using the pulse-width modulation-mode (PWM) [3] of the lamp-pumped Nd: YAG solid-state laser system. Compared to the classic-mode, "pulse-to-pulse" stability is increased by narrow-sweep control interventions. The PWM mode sets the voltage to 450 V to ensure that the laser welding system operates in the optimum (stable) operating state of the power supply. The energy input per pulse can be controlled by adjusting pulse length, spot diameter, pulse filling and frequency. In PWM mode, each pulse is segmented and fine-tuned across 10 individual sub-pulses. Due to these close-meshed feed-back interventions, the pulse power is more constant, the stability from one pulse to the next is greater and the pulses are more homogeneous. This arrangement ensures the absence of pulse peaks which could otherwise lead to a penetration of the tube walls. As a result, the seam looks more smooth and the weld pool is more stable.

The procedure to determine a parameter field for welds with and without filler metal was conducted in following manner. For welds without filler metal, the smallest spot diameter of 250 µm was selected. The requirement for an impermeable connection requires an overlap of the pulses of 75%. This sets the pulse distance to around 60 µm. The minimum selectable speed of the T-slot table in the XY plane is 10% of the maximum value, which corresponds to a speed of approximately 1.1 mm/s. Accordingly, a frequency of 18 Hz was set. The energy input was tested at intervals from lowest to highest settings using the pulse fill function with a steady pulse width of 2 ms. The experiments on joints using filler metal were performed following the same general setup. The starting laser spot size was set to 700 µm based on previous experience, which resulted in a pulse distance of around 150 µm and a frequency of 7 Hz. The pulse width was set to 3 ms and the energy input was controlled by means of the pulse fill function. For parameter combinations where the wire was merged properly to the capillary tubes the wire feeder speed was adjusted from slow to fast until a stable process was achieved.

A determination of the joint strength was carried out in tensile tests on a Zwick Z050 test machine with a modified sample geometry deviating from the standard (Fig. 2). The tested combinations were welded with the previously determined optimum welding parameters. The geometry of the specimen deviated as a result of the geometrical prerequisites of the assembly.

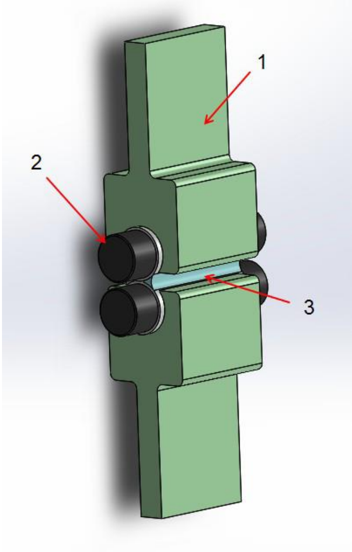

Fig. 2. Samples welded with filler wire and test assembly for tensile tests with modified sample geometry. (1) device for holding the capillary tubes; (2) calibration pin; (3) welded joint

Three diameter combinations of laser beam-welded capillary tubes with straight weld seams welded with and without filler metal were tested. Ten tensile tests were performed per diameter combination and the values were evaluated and compared.

The evaluation of the component surface were carried out using the AxioVision SE64 software on a Stemi 2000-C stereomicroscope from Zeiss AG in combination with an AxioCam MRc camera.

3. Results and discussion

3.1. Focusing conditions

With respect to the focusing conditions, the geometrical arrangement of the filler material and the capillary tubes presented some difficulties. The precise application of laser energy was strongly dependent on the diameter ratio, the shape of the joining partners and the selected wire diameter [4]. Using filler metal, a good connection required the melting of the wire and additionally the heating of the tube walls in order to create a stable weld pool and a connection to the capillary wall [5]. Due to reflection and scattering of the laser beam, the wall of the tubes is heated not only directly by the impinging laser beam but also by back-radiation, resulting in an effect of "self-focusing" in the joint (Fig. 3). When welding combinations between circular and non-circular capillary profiles, this focusing effect mostly resulted in an impermissible reduction of the wall thickness of the non-circular joining partner.

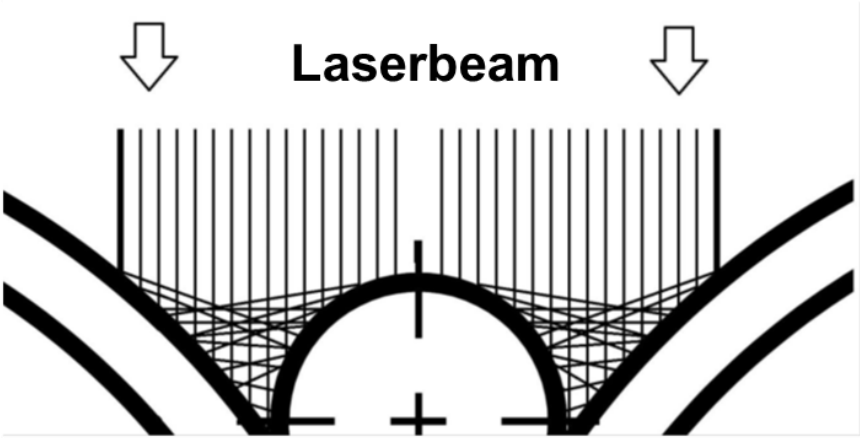

Fig. 3. Focusing conditions during laser beam welding of capillary tubes with filler material due to reflection on wire surface and tube walls

To avoid this one-sided focusing condition, diameter combination with a significant diameter difference (Figure 3.1 with r1 >> r2) or the combination of a tube with a non-rotationally symmetric geometry (Figure 3.2), must be welded under a tilting angle (α_i).

Welding tests on these combinations confirmed the necessity of pivoting the assembly out of the normal position by a specific angle (α_i) of approximately 5 degrees. This effectively prevents a one-sided shading of the joining area, as well as unilateral reflection of the laser and thus an unbalanced energy input into the joint. When filler material is used, the selected focus diameter of the laser beam is mainly determined by the diameter of the filler metal and thus by the volume of material to be melted. A small proportion of the energy input is also necessary to melt the tube walls. Regarding experiments on straight tube sections, a correlation between the diameter of the wire used as filler metal (d_{Wire}) and the focus diameter of the laser beam (d_{Spot}) in the form of $2 \times d_{wire} + 100\ \mu m = d_{Spot}$ was determined for this laser system.

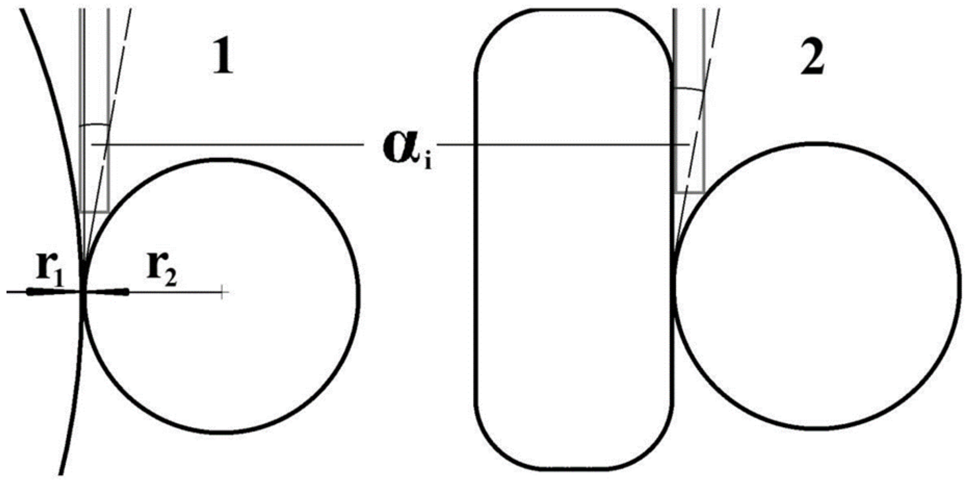

Fig. 4. Process control in laser beam welding of capillary tubes with (1) large diameter differences or (2) non-circular profiles using a tilting angle α_i compared to the welding position PA (flat position)

3.2. Welding Parameters

The most common diameter combinations were a 3.00 mm tube with 4.05 mm tube or a 1.50 mm tube. Consequently, most experiments were performed on tubes of this dimensions.

For the diameter combination of a 3.00 mm tube (wall thickness 0.14 mm) with a 4.05 mm tube (wall thickness 0.15mm), the optimum energy input to produce a high-quality weld seam was set to 3.8 J per pulse with a spot size of 700 µm and a pulse width of 3 ms. The pulse energy was more than twice higher compared to the process without filler material. This can be directly attributed to the use of filler metal, since additional energy is needed to melt the wire and the tube walls. Therefore, more energy must be applied with a spot diameter exceeding the wire diameter. The visual inspection of the joint showed a flawless weld seam with no visible binding defects.

Further experiments with other diameter combinations and wall thicknesses showed that with an increasing capillary diameter of up to 4.5 mm, the focus diameter can be increased to about 850 µm. For smaller diameters in the range of 1.5 mm, a focus diameter of 600 µm is recommended. The possible pulse energy lies between 3.2 and 4.0 J depending on the tube wall thicknesses. With respect to the geometrical conditions in the joining area, the selection of a small spot size, which is adapted to the wire diameter, appears appropriate.

The use of filler metal influences the position and size of the parameter field for the welding process. The coordination between the wire feed speed and the welding speed was a significant parameter. For a wire diameter of 300 µm, a wire feed rate of about 115 percent of the welding speed was found to be optimal. If the wire feed rate is too high, there is a risk of immersion into the weld pool and unintended contact with the capillary walls, resulting in an unstable welding process. If the wire feed rate is too low, the wire tip may lose contact with the weld pool, resulting in imperfections of the weld seam. Table 1 below shows the identified welding parameters for different capillary tube diameters.

Table 1. Optimum welding parameters for welding straight and bent seams with filler metal

Diameter combination	3.00-1.50 mm	3.00-3.00 mm	3.00-4.05 mm	4.05-4.05 mm
Spot size	700 µm	800 µm	700 µm	700 µm
Pulse width	3 ms	3 ms	3 ms	3 ms
Pulsefill	43 %	43 %	43 %	43 %
Pulse distance	140 µm	200 µm	100µm	120 µm
X-Y Speed	1.5 mm/s	1.5 mm/s	1.5 mm/s	1.5 mm/s
Frequency	11 Hz	8 Hz	15 Hz	13 Hz
Wire speed	1.7 mm/s	1.7 mm/s	1.7 mm/s	1.7 mm/s
Tilting angle	5°	-	5°	-

3.3. Tensile test

When comparing identical diameter combinations which have been welded with and without filler metal, the maximum tensile forces of the joints welded with filler material are 25 to 35 percent higher in average. Therefore, a tensile strength of the connections with filler metal can be achieved which is in the range of the base metal (Fig. 5).

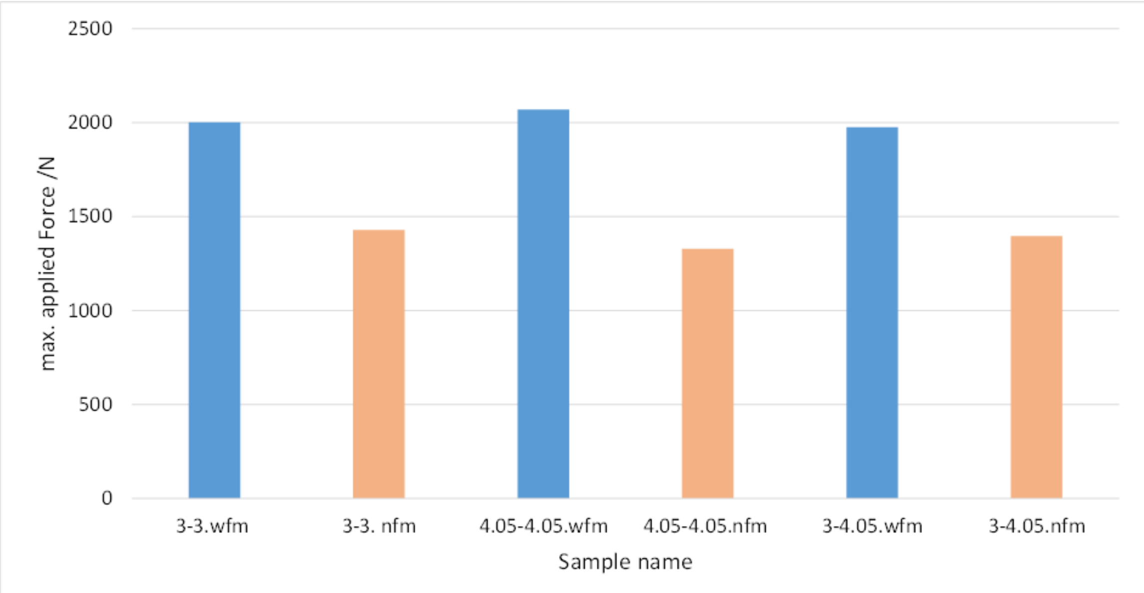

Fig. 5. Maximum tensile forces of the test series with different diameter combinations of capillary tubes for laser beam welded joints, with (wfm, shown in blue) and without (nfm; shown in orange) filler metal

The samples welded with filler metal failed as expected in the thermally influenced region of the capillary tubes, the heat affected zone, next to the weld seam. As a result of the manufacturing process, the capillary tubes, made from the austenitic chromium-nickel steel 1.4301, are more or less strain-hardened depending on the delivery state before welding. Due to the local heat input during laser beam welding, the strain-hardening in the contact zone of the weld is partly or completely eliminated, which explains the location of the fracture in this area. Micro-hardness measurements on capillary tubes in the base material, the weld seam and the heat affected zone confirmed this explanation.

3.4. Metallographic cross sections

Cross-sections were prepared for optical microscopy using standard procedures including grinding, polishing and etching. The advantages of using filler metal can also be seen in metallographic cross sections of laser beam welded joints with straight seam course. By applying filler metal in the laser welding process, a reduction in wall thicknesses along the connection area could be completely avoided (Fig. 6). The right figure shows a weld seam without filler metal. The wall thickness of this connection is reduced by about 40 percent compared to the initial state. The left figure shows a weld accomplished with filler metal. There was no reduction in wall thickness.

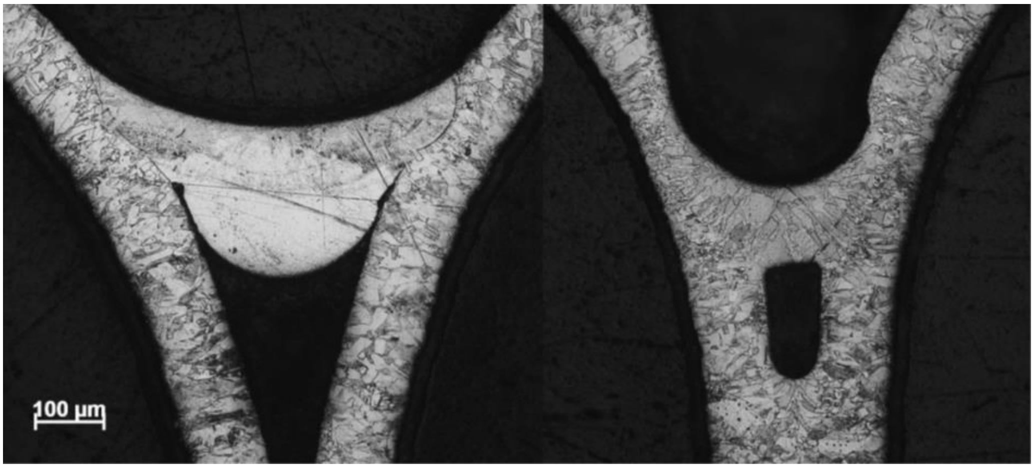

Figure 6. Cross-sections of laser beam-welded capillary tubes of the same diameter / left with filler metal; right without filler metal and with reduced wall thickness

3.5. Visual inspection

The quality of the weld was evaluated according to the valid laser weld quality standard EN ISO 13919-1, where the weld quality is based on levels B, C, D and rejected quality [6]. Without the use of filler metal, annealing colours on the inside wall of the tube were apparent. By using filler metal, the surface of the capillary tube did not show any oxidation in the welding area and no annealing colours along the inside of the tubes. The filler material wetted both seam flanks in the area of the weld seam top, resulting in an even and clean seam contour.

4. Outlook and first results – welding of bent capillary tubes

The determined parameter envelope was transferred from straight welds to curved weld seams with and without the use of filler metal with comparable parameters. Bent capillary tubes have significantly greater tolerances as a consequence of the bending process, which in turn leads to greater joint tolerances. As such, gaps between joining partners in the region of the bent are possible. When welding without filler metal, these tolerances often results in an impermissible reduction of the initial wall thickness of up to 20 percent and a partial penetration of the tube walls. Taking this aspect into account, further experiments on bent joint courses were only conducted using filler metal to bridge the gap between the capillary tubes.

When welding bent capillary sections, it is important that the bending radius of the tube geometry is as uniform as possible. With respect to the very narrow tolerance field of the laser beam welding process, an optimized and mechanized bending process is therefore indispensable, especially for welding in series production. Particular attention had also be paid to the positioning of the filler metal wire. If the wire is positioned only slightly out of alignment, it may merge only to one side of the joining partners [7]. The contact point of the wire and the capillary tubes has to be directly in the area where the laser spot impinges upon the material in order to produce a weld pool. In the case of curved seams, the work angle and the free wire end has to be positioned in such a way that the additional material is conveyed exactly into the seam course. Even slight deviations may lead to the wire getting fed out of position in the bent section. For bent capillary tubes, which meet the narrow tolerance range, and with exact positioning and adjustment of the wire feeder, a partially automated welding process can be implemented.

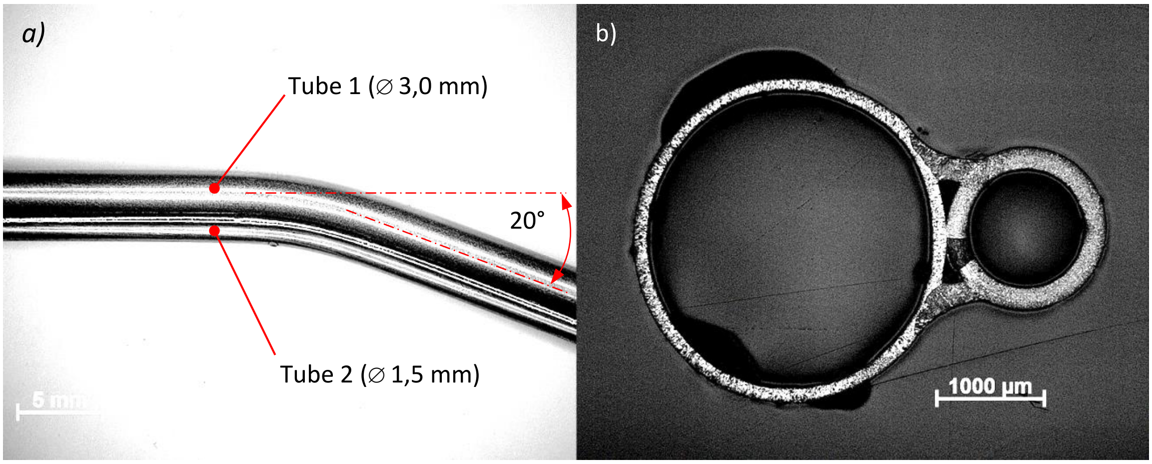

Fig. 7. a) Stereomicroscope picture of capillaries with a diameter combination of 3.00 mm - 1.50 mm bent by 20 °;
(b) cross-section of the joint is taken from the bent area

The results show that with adequately formed capillary tubes, a semi-automated laser welding process could be carried out. The material surface of the cannula did not show any oxidation in the welding area. Visual inspection indicated, that the filler metal was well connected to both seam flanks and showed a uniform and clean seam contour. The cross-section of the connection shown in Figure 7b confirmed this observation. The filler material wetted the seam flanks and no gap could be seen between the two parts. It could be ascertained that the use of filler metal efficiently and reproducibly prevents any damage and oxidation of the inner wall surface or thinning of the tube walls. Using filler metal assures a more stable laser welding process making it possible to bridge small gaps resulting from the tolerances of the bending process.

5. Conclusion

Thin-walled capillary tubes were welded reproducibly and according to requirements using filler material. It was possible to partly automate the welding process of straight and curved seams. With the use of filler metal, the joint area was increased compared to welds without filler metal. As a result, the maximum permissible tensile force of welds with filler material is about 25-35% higher than without. In addition, the use of filler metal prevents any damage or thinning of the tube wall.

Further investigations will focus on an increased automation of the process and a reduction of the automatically fed wire diameter. With a substantially smaller diameter (e.g., 0.1 mm), a smaller spot size would be possible resulting in a more precise energy input into the joint.

Acknowledgement

We would like to thank the Federal Ministry for Economic Affairs and Energy (BMWi) for its financial support of the research project "Laser beam micro welding of cannula tubes for medical products with supplementary material support". This project was carried out under the auspices of the German Federation of Industrial Research Associations (AiF) within the Central Innovation Programme SME. The thanks also go to the research and industry partners for the intensive cooperation and professional support.

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Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

References

[1]H. Van Benthem; Advantages of laser welding compared to conventional joining; Die Quintessenz der Zahntechnik; vol. 17, 1991, pp.1178–1193

[2] Füll, G. : Laser - das noch unbekannte Werkzeug; Fertigung 17 (1990) 9, pp. 63-72

[3] G. E. FENNER; US-Patent; Pulse width modulated laser US 3478280 , 1969

[4] Z. Sun, A.S. Salminen; Current status of laser welding with wire feed; Mater. Manuf. Process., 12 (5) (1997), pp. 759–777

[5]A.S. Salminen, V.P. Kujanpää, T. Moisio; Beam-wire interactions during laser welding with filler wire; Weld. J., 75 (1) (1996), pp. 9–13

[6]EN ISO 13919-1**:** Welding – Electron and laser-beam welded joints – Guidance on quality levels for imperfection – Part 1

[7]U. Dilthey, D. Fuest, W. Scheller; Laser welding with filler wire; Optical and Quantum Electronics 27 (1995), pp.1181-1191