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Rotary straightening of fine wire for LMD-W applications

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Abstract

In wire-based high-precision laser applications as micro welding or micro laser metal deposition the straightness of the wire used plays an essential role. Small process windows require constant input conditions and thus straight wire without deformations. Uncoiled commercial wire exhibits a spatial, often helix-like curvature as a result of previous recoil processes on comparatively small reels. With the rotary straightener developed in this work, stainless steel wires with diameters of 75 µm and 100 µm, respectively, were straightened from average curvature levels of 22.56 m^{-1} down to 0.61 m^{-1} by alternating bending. This cold forming process causes crystallographic irregularities (dislocations) and residual stresses, which additionally lead to a rise in hardness and yield strength of the wire. For subsequent laser processes the changed material properties are advantageous, as they increase process robustness and enable a longer wire stick-out.

Keywords: micro welding; laser metal deposition; fine wire; rotary straightener; alternating bending

1. Introduction

In addition to the wide range of uses, from air coils to brushes and woven filters or nets, fine wire is increasingly becoming the subject of investigations in the field of wire-based laser metal deposition (LMD-W). A prerequisite for a reliable manufacturing process in this size range are minimally varying environmental conditions; this applies in particular to the straightness of the wire used. Drawing and annealing processes during manufacture cause residual stresses in the wire; Kim et al., 2008. Moreover, commercially available fine wire is often coiled and shipped on reels with a comparatively small radius. After uncoiling, the wire exhibits a spatial, often helix-like curvature. For the majority of end users, this does not pose a problem as the wire is given its intended shape in further processing steps. However, in LMD-W the wire is fed directly from reels

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into the laser process zone. This requires prior straightening of the wire which is state of the art for wire diameters from 300 µm upwards. There are various definitions of fine wire; we will consider wires with a diameter of or less than 100 µm as fine wire – sometimes referred to as microwire – in the following.

In general, there are two methods for straightening wires: roller straightening and rotary straightening. In both, the goal is to compensate for the mechanical stresses present in the wire through multiple bending transformations. The roller straightener typically contains a series of guide rollers arranged in two parallel rows offset from each other. As the wire passes the straightener, it is subjected to alternating bends in one single axis beyond the elastic limit. Often, several of these devices are arranged in cascade, with the effective axes rotated 90° or 120° from each other. Relevant parameters are the number of guide rollers, their distance to each other and the offset from the central axis of each roller; Schuler, 1998.

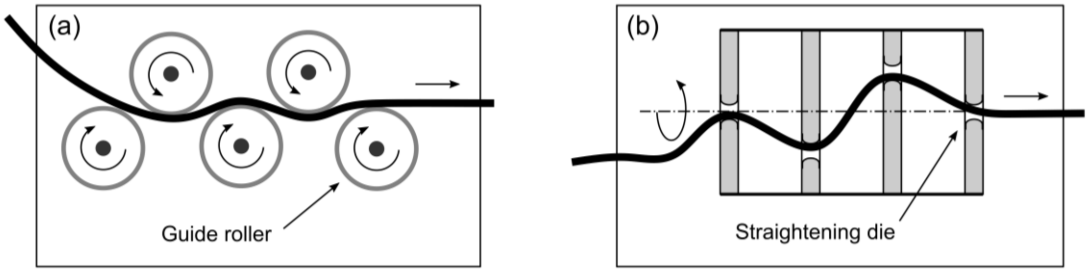

Fig. 1. (a) Roller straightening, note: the guide rollers are not actively driven; (b) rotary straightening.

In contrast to bending on discrete axes, rotary straightener allow bending in an overlapping helical pattern. The principle of operation and the relevant parameters are similar to that of roller straighteners, but instead of guide rollers, straightening dies are used which revolve in a suitable manner around a central axis. The number of alternate bends depends on ratio of wire feed velocity and number of arbour rotations. Due to the rotating bending axis, high straightness can be achieved with rotary straighteners. The drawbacks of using this straightener type are possible damage to the wire surface and twisting of the wire during the operation. While it is irrelevant for sectional straightening with subsequent cutting, it plays a major role for continual processing; Patel and Prajapati, 2011.

Apart from these two established straightening methods, approaches to thermal straightening of fine wire exist. Yamashita and Yoshida studied the effect of cold and warm tensile straightening on gold, copper and stainless steel wires with a diameter of 25 µm. In this process, wire under tension passes through a furnace; no information was provided on the type of heating. As the temperature under tensile load increased, the straightness of the wires was found to increase as well. However, a too high tensile load had a detrimental effect; Yamashita and Yoshida, 2005. A similar setup was used by Kim et al. Instead of going through a furnace, a 100 µm diameter tungsten wire was passed through a glass chamber flooded with argon. By applying an electrical voltage across two electrodes, the wire in the chamber was heated up to 973 K. Suitable parameter combinations resulted in a straightness of 1 µm/1000 µm; Kim et al., 2006. Tsurumi et al. combined tension annealing with upstream twisting of AISI 304 stainless steel wire; the twist was created by a rotating blade. After annealing at 773 K under tension load, a straightness of $1.81 \cdot 10^{-6}$ mm^{-1} with a wave height of 0.117 mm could be achieved for wire with a diameter of 350 µm; Tsurumi et al., 2013. Even if satisfying results can be achieved with the above-mentioned thermomechanical straightening methods, their set-up and implementation is complex in relation to bending methods.

2. Experimental

2.1. Wire straightening

The developed wire straightener is based on the principle of rotary straightening. Coming from a reel, the wire passes first through a hollow shaft motor and then through holed plates, which are driven by the hollow shaft motor and at the same time offset the wire from the central longitudinal axis. The plates have several holes next to each other, so that this offset can be adjusted in steps. The distances between the plates are also adjustable. After passing through the straightening unit, a large diameter reel coils the wire. This second reel is actively driven. To prevent the wire from being coiled twisted, the hollow shaft motor is operated alternately in opposite directions of rotation. If necessary, the speed of the wire can also be adjusted to the angular speed of the arbour. This means that at the reversal points of the direction of rotation, the wire is stopped. An additional tensile load is applied by decelerating the first reel in a defined manner. All experiments were performed with the following parameters: Rotational speed 13.3 s^{-1}, rotational acceleration 25 s^{-2}, offset from central axis 8 mm, distance between plates 30 mm, wire speed 10 mm/s, and tensile load 1.8 N.

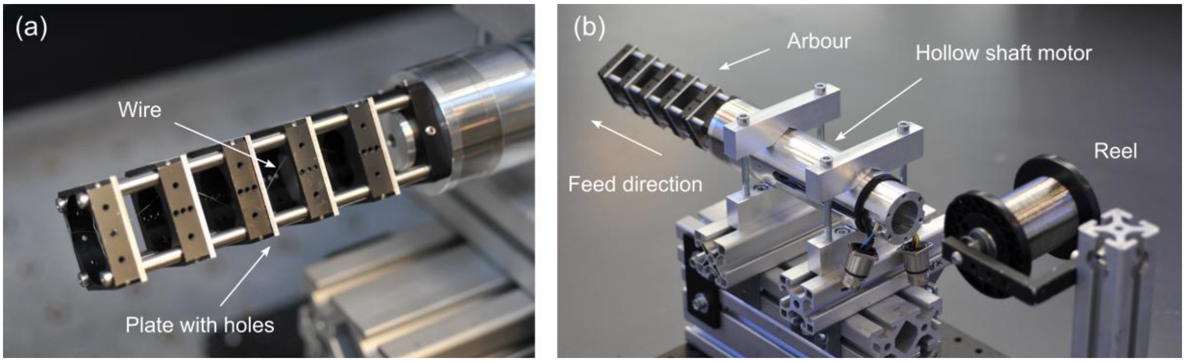

Fig. 2. Rotary straightener developed in this work, the second reel is not pictured.

The experiments were carried out with wires of diameters 75 µm and 100 µm, with the thinner wire made of 1.4301 (AISI 304) and the thicker wire made of 1.4401 (AISI 316). For both, the chemical composition was determined by energy-dispersive X-ray analysis is shown in Table 1.

Table 1. Chemical composition of fine wires used in this work.

Wire diameter	Material	Si	Mo	Cr	Mn	Ni	Other
75 µm	1.4301 (AISI 304)	0.53 wt%	0.70 wt%	18.48 wt%	1.55 wt%	8.59 wt%	balance
100 µm	1.4401 (AISI 316)	0.53 wt%	2.25 wt%	16.97 wt%	1.39 wt%	11.16 wt%	balance

2.2. Measurement of wire curvature

Several approaches exist to determine the straightness or, respectively, the curvature of wires: the number of concavities and convexities on suspended wires segments of equal length can be counted; the radius of wire with helix-like curvatures can be determined by start, middle and end point for sections of certain length; machine vision measurement methods can be used to reconstruct the wire shape and derive the curvature information; Yamashita and Yoshida, 2005; Eriksson et al., 2018; Sun et al., 2001. When the wire curvature varies over a wide range from wire to wire, the above methods reach their limitations. In this work, a flatbed scanner was used to capture the geometry of the wires under investigation before and after the straightening process. The uncoiled, unstraightened wire was curved in two dimensions and to different degrees. By closing the scanner lid, the wire was forced in a flat constrained position where parts of the curvature information may get lost. According to this procedure, ten segments, each approximately 20 to 30 cm long, of unstraightened and straightened wire with diameters of 75 µm and 100 µm were scanned with three repetitions. At a resolution of 2400 ppi, there are theoretically seven pixels available to display a 75 µm wire. The pixels that represent the wire were assigned corresponding coordinates after calibration, so that the geometry was available as pairs of coordinate values for further evaluation.

3. Results and discussion

3.1. Effect of straightening on the wire material

Based on SEM images, the following changes of the wire could be observed (Figure 3). By measuring on three different wire segments, each with three repetitions, it was found that the diameter of the wires decreased from 100.1 µm ± 0.1 µm to 95.1 µm ± 0.1 µm and from 75.2 µm ± 0.1 µm to 73.2 µm ± 0.1 µm. This change was caused by the tensile load during the straightening process. Furthermore, the wires had stripe-like

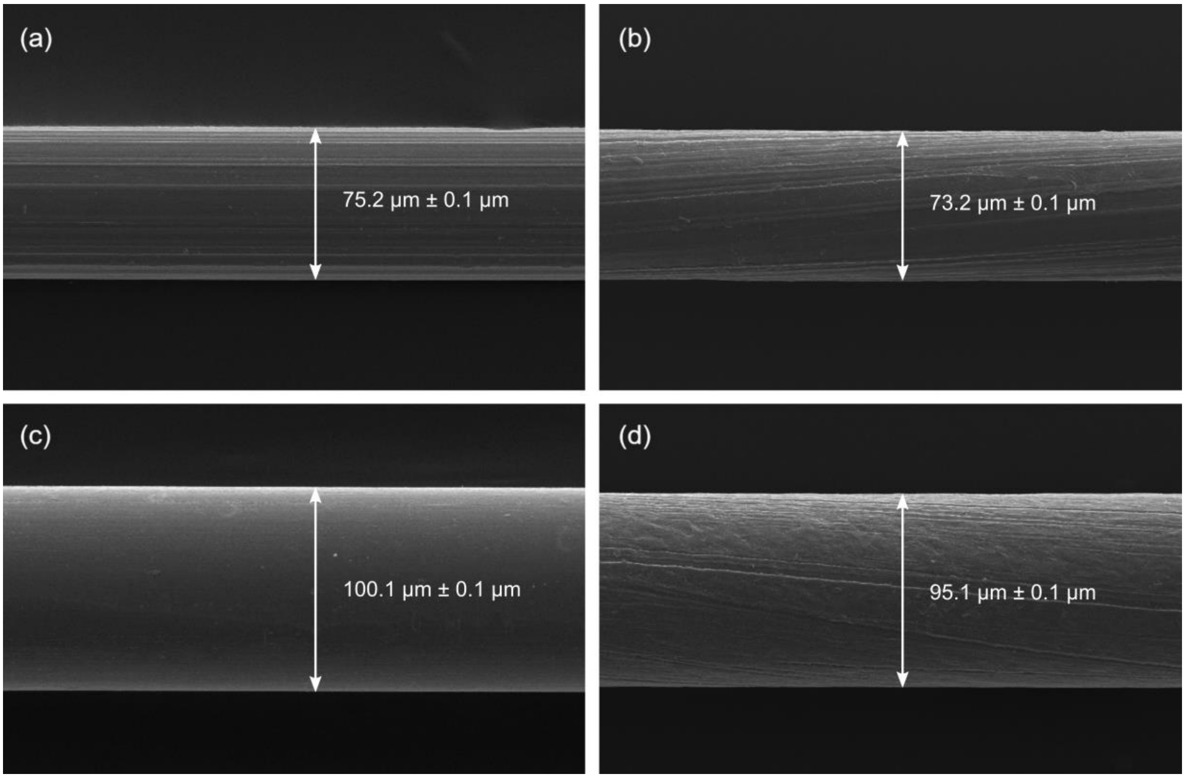

Fig. 3. SEM images of unstraightened (a, c) and straightened wires (b, d).

marks on their surface. While some of them are production-related due to the drawing process (75 µm wire), others were formed when the wire passed through the revolving dies of the straightener. Since the wire is twisted to different degrees between the two reels during straightening, several of these marks with different pitches can occur. The presence of circumferential strip marks does not necessarily mean that the wire is twisted in this section. The straightening process is set in such a way that the wires can be coiled without twisting. This was confirmed by the fact that the coiled, straightened wire did not twist back immediately after cutting, as previously observed. For the intended use in LMD-W, the observed changes in the surface play a minor role.

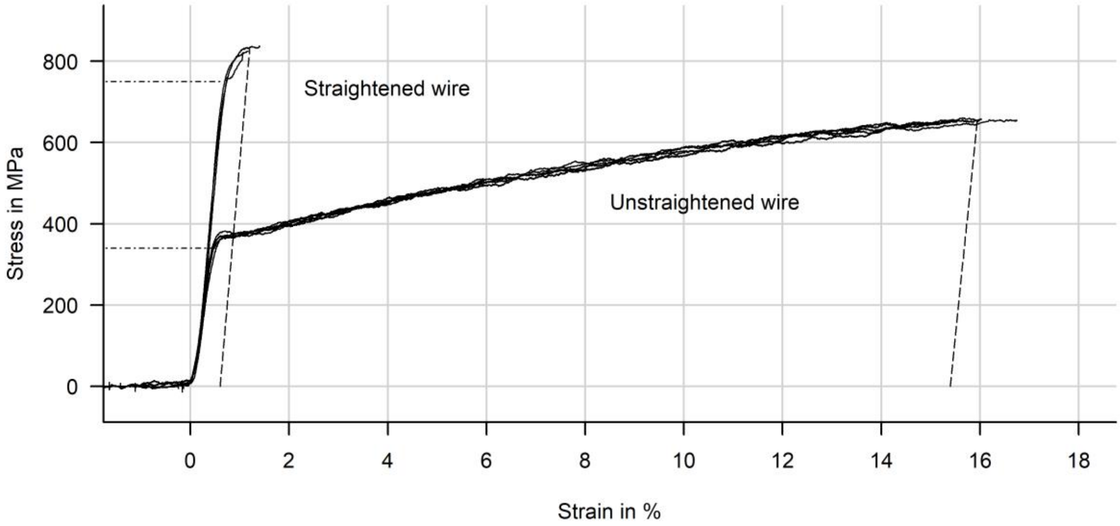

Fig. 4. Results of tensile tests with four straightened and five unstraightened wires.

Tensile tests with 100 µm wires revealed that the straightened wire had changed mechanical load capacities. On the one hand, the yield strength increased from 340 MPa to 750 MPa. On the other hand, the unstraightened wire showed a pronounced ductility, while fracture occurred early in the case of the straightened wire. This is represented by a decrease in breaking strain from 15.4 % to 0.6 %. Figure 4 shows the stress-strain curve resulting from tensile tests with four straightened and five unstraightened wires. In addition, it was found that the Vickers hardness at the wire surface increased from an average of 150 HV 0.02 for unstraightened to 225 HV 0.02 for straightened wires.

Following Anderson et al., the reason for this behaviour is work hardening due to bending deformations beyond the elastic limit during the straightening process, in which the metallic crystal structures are compressed or stretched. As a result, the dislocation density increases in these crystal structures. Since dislocations hinder each other in their movement, a higher mechanical stress is required for further deformation. When the dislocations can no longer move, fracture occurs. The effect of work hardening is reversible: At temperatures of about 0.3 to 0.4 times the melting temperature of the material, recovery takes place; Anderson et al., 1990. In practice, this means that an increase in yield strength through work hardening is always accompanied by severe embrittlement of the material. However, the advantages of higher strength outweigh the disadvantages, as higher elastic deformability is beneficial for the LMD-W process. In detail, this concerns the process robustness and the wire stick-out, i.e. the distance between the end of the wire guide tube and the position of melting by the laser radiation (cf. Figure 7). As our preliminary studies have shown, the wire does not melt continuously, so bending stresses occur during the LMD-W process. Due to the increased strength, the wire can therefore be subjected to higher loads.

3.2. Determination of wire curvature

After scanning and assigning coordinates, the wire geometries were available as pairs of values. For further calculation it is helpful to consider the wire geometries as continuous curves whose coordinate pairs are ordered according to the path along the curve. The reordering was done by applying an algorithm to find the shortest route between two endpoints under the condition that all other points are also part of the route (cf. travelling salesman problem). This results in polygons whose curvatures were calculated piecewise as follows:

$$\kappa = \frac{4 \cdot F}{a \cdot b \cdot c} \qquad (1)$$

with κ being defined as the inverse radius of a circle, on which three successive points of the polygon lie. *F* is the area of the triangle formed by the three points, and *a*, *b*, and *c* are its three sides. The discrete curvatures determined in this way are only suitable to a limited extent for comparing different wire curvatures. Considering *ds* as the average of the length of two neighbouring polygon edges one can use as a measure:

$$K = \frac{\sum|\kappa| \cdot ds}{\sum ds} \qquad (2)$$

The average curvature *K* of all investigated unstraightened wires was found to be 24.17 m^{-1} ± 2.13 m^{-1} for 75 µm wires, wheras it was 20.59 m^{-1} ± 1.82 m^{-1} for 100 µm wires. After straightening, the wires had a

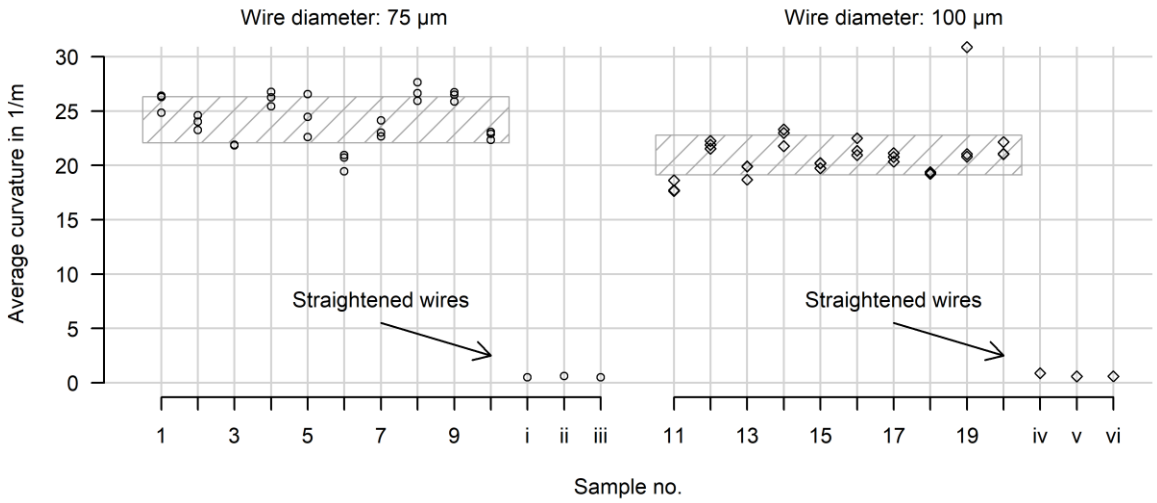

Fig. 5. Average curvature of unstraightened wires (sample nos. 1 to 20) and straightened wires (sample nos. i to vi) with diameters of 75 µm (left) and 100 µm (right). The hatched rectangles mark the area of the mean value ± standard deviation of the samples.

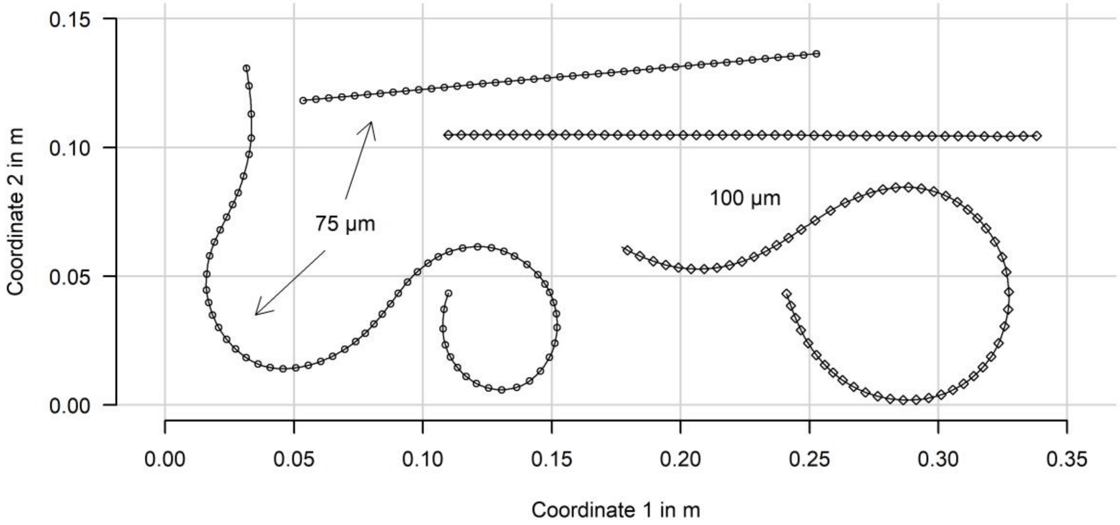

Fig. 6. Scanned geometries of wire sample nos. 1 & i (75 µm) and 12 & iv (100 µm), cf. Figure 5.

curvature of 0.53 m^{-1} ± 0.07 m^{-1} and 0.69 m^{-1} ± 0.17 m^{-1}, respectively. The results are shown in Figure 5. In purely mathematical terms, for instance, an ideally straight 75 µm wire with a yield strength of 750 MPa and a Young's modulus of 117 GPa can exhibit a curvature of up to 171 m^{-1} in the elastic state. Here, the wire was considered as a beam with a constant bending radius. Due to static friction of the wire surface with the scanner glass, the wires can deform slightly elastically both during placement and subsequent closing of the lid. This should be taken into account when interpreting the measured values and depicted geometries. Figure 6 shows the scanned geometries of two unstraightened and two straightened wires of 75 µm and 100 µm diameter, respectively.

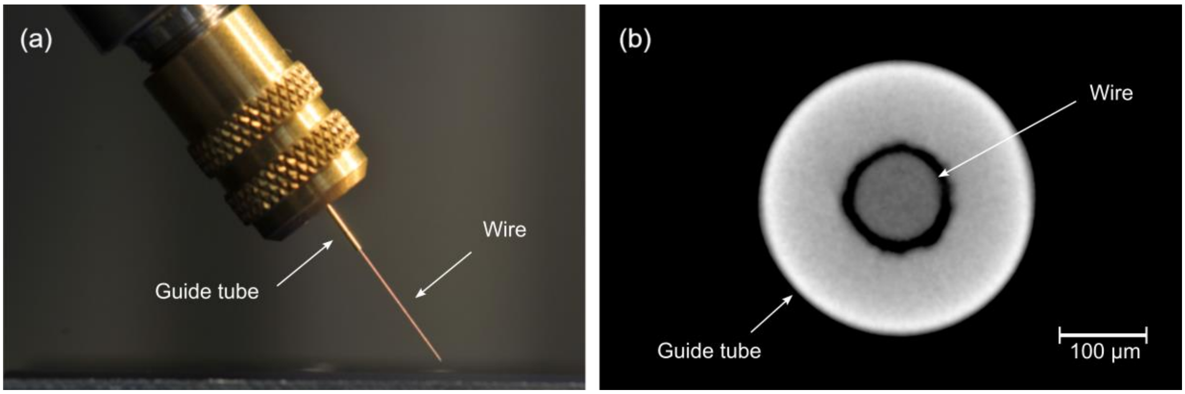

Fig. 7. (a) Detail of a wire feed drive with guide tube and straightened fine wire; (b) cross section of the guide tube and the fine wire within (SEM image).

4. Conclusion and outlook

A simple but effective approach to straightening fine wires has been demonstrated in this work. Based on the results of the investigations, the following conclusions can be drawn: Rotary straightening is a suitable method for straightening fine wires. The average curvature of commercial stainless steel wires with diameters of 75 µm and 100 µm could be decreased to 0.53 m^{-1} and 0.69 m^{-1}, respectively. Only visually apparent in SEM images, the influence on the surface quality was comparatively small. The developed method of alternately rotating the straightening arbour in opposite directions in order to counteract twisting of the wire has proven to be successful. Directly afterwards, the straightened wire could be wound onto a large diameter reel.

The demand for high straightness of fine wires for the envisaged LMD-W is particularly evident from Figure 7. Equipped with a guide tube, a part of a wire feed drive is shown on the left hand side with a wire sticking-out approx. 12 mm. Strong curvatures of the wire inevitably lead to different impact points on the substrate and thus to different laser irradiation conditions. In addition to the problem of feeding the wire to a defined point, the difficulty arises with curved wires of moving them through the guide tube with as little friction as possible. On the right hand side of Figure 7 the guide tube with the fine wire inside is shown. The distance between them is 10 µm.

Future work will investigate further optimization of the straightening parameters in order to increase throughput on the one hand and to be able to process even thinner wires of different materials down to a diameter of 50 µm on the other.

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