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Feasibility study on laser rod end melting of stainless-steel microtubes

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Abstract

Laser rod end melting is a process to generate a wire end finish in micro range, wherein the laser induced melt forms nearly spherically due to surface tension. The solidified melt, called preform, can e.g. further be shaped by forming. At present, this process has been successfully used in wires of stainless steel and Nitinol, with the wire diameters below 1 mm. In this paper this process is applied on stainless steel (1.4401) microtubes with 0.8 mm outer diameter and 0.25 mm inner diameter to determine the process window for forming hollow preforms. The differences compared to processing of wires is discussed and the general feasibility of laser rod end melting of microtubes is proven.

Keywords: Laser beam machining; Stainless steel; Free forming

1. Introduction

Laser rod end melting (LREM) is a thermal process to create a melt drop at the end of a rod. By using a scanned laser beam, a wire end is melted, resulting in the formation of a spherical accumulating melt due to the balance between surface tension and gravitational forces. This melt subsequently solidifies to form a preform. Previously, studies have successfully utilized LREM combined with cold forming (Brüning & Vollertsen, 2015) or immediate flange processing (Lu & Radel, 2022) to fabricate cone-shaped and cylindrical micro flanges from stainless-steel and Nitinol wire, respectively. These preforms on the wire end can be potentially used as push-pull cables in actuator device such as biopsy forceps, where the wire end acts as an anchor for the forceps, which can be actuated through mechanical or thermal means. Besides the wires, the LREM has been applied

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on thin sheet rim and voids in metal sheets. This results in the formation of continuous cylindrical preforms at the rim for the protective purpose or at voids for collar forming (Vollertsen et al., 2020).

The objective of this study is to explore the feasibility of applying the LREM to stainless-steel microtubes to generate hollow preforms. This is conducted by filling argon gas into the capillary during the process and inspired by the glassblowing process. The resulting hollow structure has the potential of container functionality for micro heat pipe (Zohuri, 2020). The fabricated preforms were characterized in terms of surface topography, microstructure, and material distribution, considering the influence of gas flow rate.

2. Methodology

The experimental setup is schematically depicted in Fig. 1. In this study, the LREM was applied to stainless-steel microtubes (1.4401, Reichelt Chemietechnik GmbH) and stainless-steel wires (1.4301, CRW-Feindraht GmbH). The microtubes had a 0.8 mm outer diameter and a 0.25 mm inner diameter, while the wires had a diameter of 1 mm. The process was carried out in a hemi-sealed chamber filled with nitrogen gas, with a pressure of 3 bar maintained for 40 seconds prior to the laser melting. A plastic tube was sealed at one end of the microtube to facilitate the delivery of modified argon gas. The gas flow was regulated using a flow ratio controller (MKS 647B, MKS Instrument Deutschland GmbH) to maintain a constant flow rate through the process. The argon gas had an input pressure of 3 bar prior to the regulation, and various gas flow rates were tested to generate preforms of varying volumes. Similarly, the LREM of wires were conducted under the same shielding gas condition as a reference.

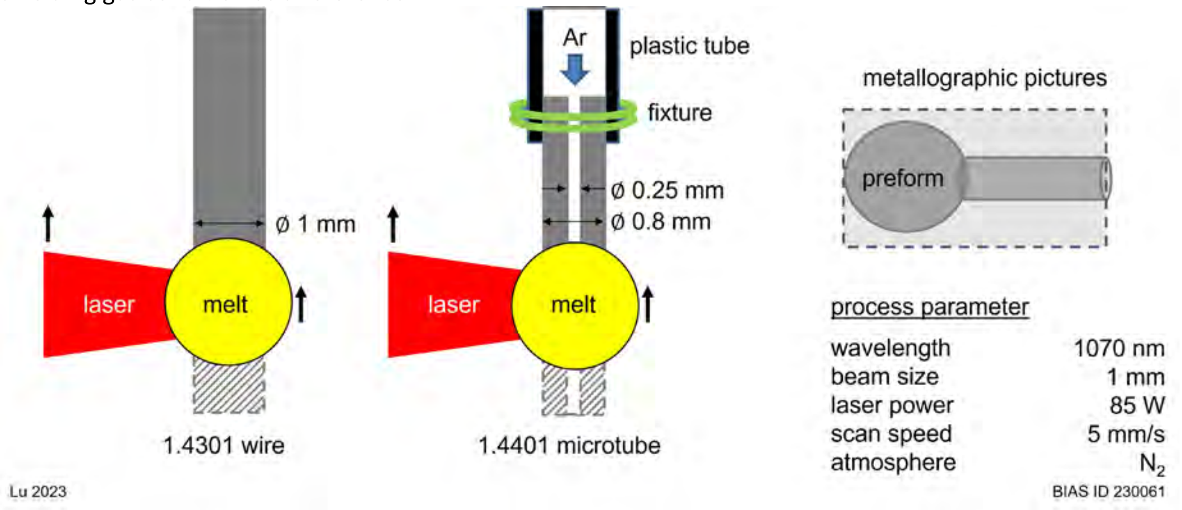

Fig. 1. Schematic depiction of the experimental setup for laser rod end melting of wires (left) and microtubes (right)

Prior to the LREM, both the wires and microtubes were cleaned with ethanol. They were fed through an alignment system into the process chamber, ensuring their placement in the laser scanned area. A continuous wave laser (YLR-100-AC, IPG Laser GmbH) and a deflection unit (AXIALSCAN-30, RAYLASE GmbH) were used for the LREM, with the laser beam laterally applied to the end of the microtubes or wires, as illustrated in Fig. 1. The laser was defocused to obtain a spot size of 1 mm (SP300, Ophir Spiricon Europe GmbH) on the microtube or wire. The focal position was set behind the target material, ensuring that the melt received uniform irradiation and reducing the eccentricity of the preform caused by Keyhole formation (Brüning et al., 2016). During the process, the wires and microtubes remained static, while the laser moved upwards at a constant scan speed of 5 mm/s and a laser power of 85 W. Each process parameter was repeated three times to ensure the reproducibility. The fabricated preforms were firstly characterized by an optical microscope (VHX-7000, Keyence Deutschland GmbH) to examine the surface topography. To analyze the material and microstructure distribution, longitudinal sections were prepared. These sections were embedded in acrylic resin, followed by polishing and etching with a Kalling's etchant for several seconds. The selected graphics were representative for each process parameter.

3. Results

Fig. 2 shows the effect of argon gas flow rate on preform generation. First, excessive gas flow rates at and exceeding 170 cm^3/min resulted in the bursting of accumulated melt due to too strong gas flow. The micrographs comparing preforms with and without gas filling revealed comparable surface topography. The preform surface displayed a distinctive roughness characterized by stripe-shaped pattern. No visible defects such as dimples or cracks were observed. Regarding the preform geometry, the metallographic images (see three bottom pictures in Fig. 2) reveal the eccentricity of the preform. In addition, the preforms exhibit an ellipsoidal shape rather than a spherical one.

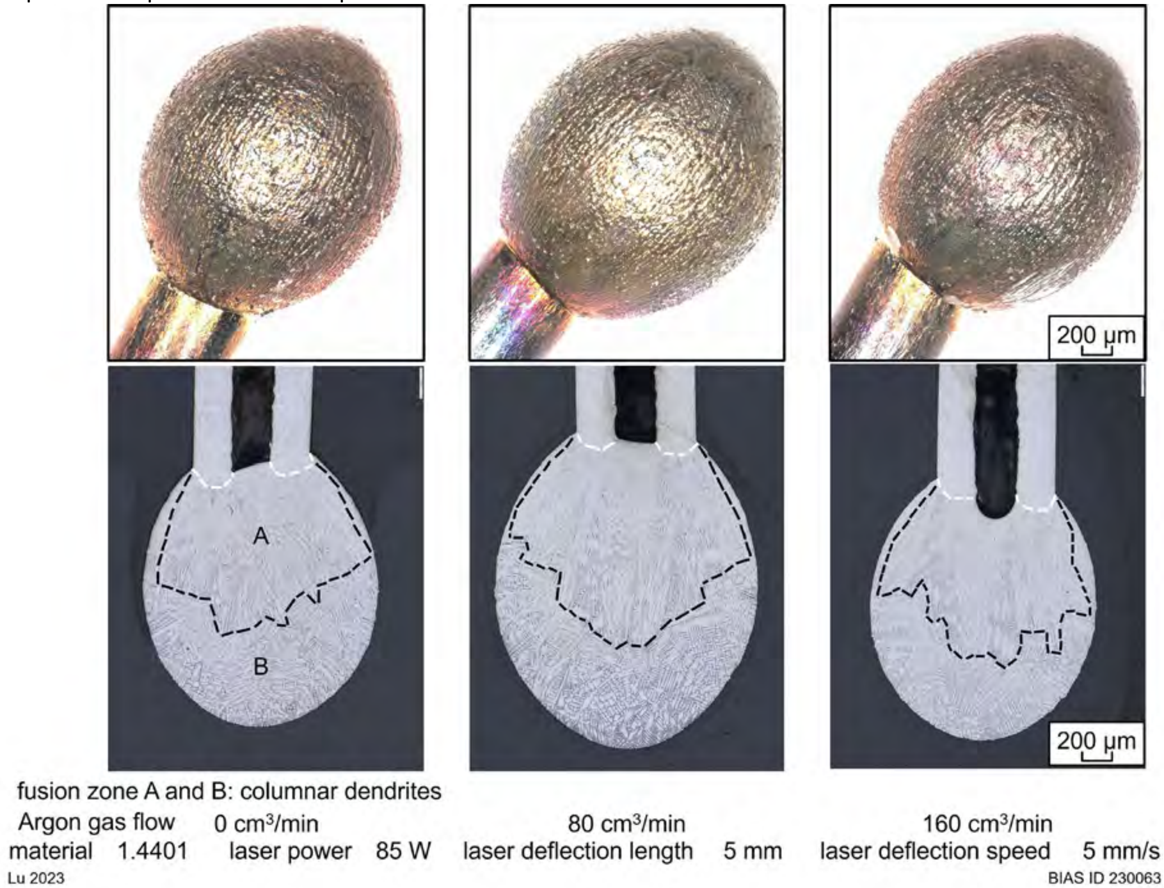

Fig. 2. Surface topography and microstructure of longitudinal section of preform fabricated from stainless steel microtubes.

Furthermore, the metallographs in Fig. 2 present solidified preform under varying gas flow rate. Without gas filling, the melt entered the microtube. With a flow rate of 80 cm^3/min, the extent of the melt filling in the microtube was reduced. When the gas flow rate reached 160 cm^3/min, instead of large cavities or individual pores, a hemispherical opened void, with a curvature diameter comparable to the microtube inner diameter, was observed on the side of the preform. Regarding the microstructure, two distinct fusion zones A and B with columnar dendrites were distinguished based on the solidification direction, depicted by a black dashed line. The dendrites in both fusion zones exhibited a grain orientation towards the solidification direction.

Using a constant gas flow rate of 160 cm^3/min, preforms of varying volume were fabricated from microtubes with different molten lengths, compared to the preforms from the reference wires. Fig. 3 presents the longitudinal microstructure distribution of these preforms. Similar fusion zones and grain orientation, as described in Fig. 2, were observed in the preforms fabricated from the microtubes and wires. In addition, the hemispherical opened voids, observed in Fig. 2, were also found in the preform with varying volume.

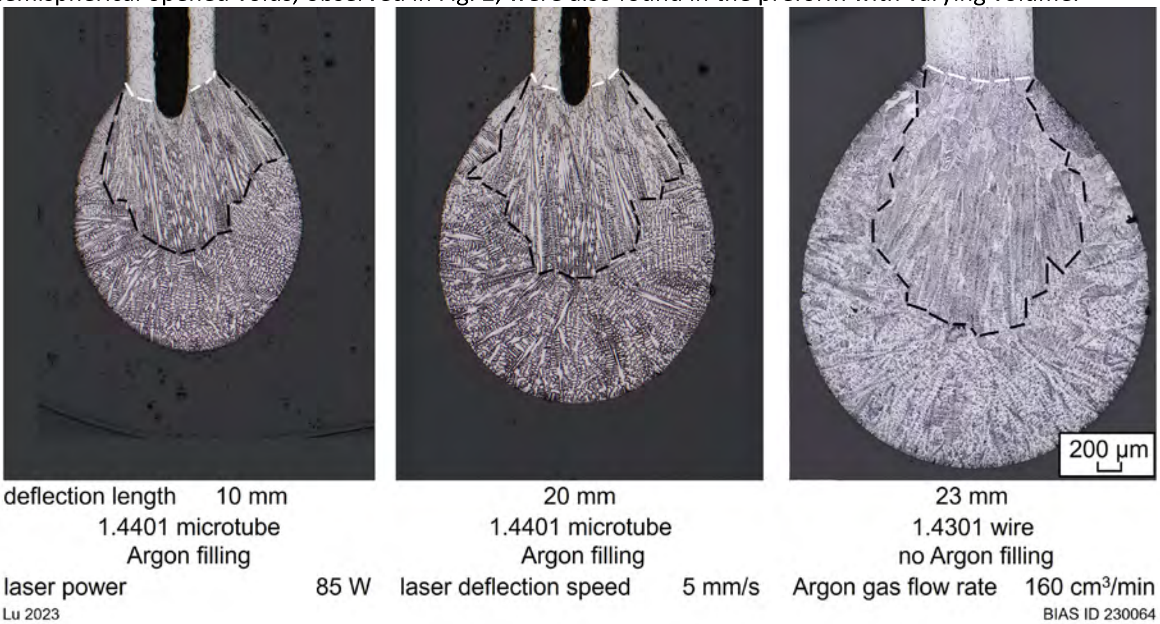

Fig. 3. Longitudinal section of preforms fabricated from stainless-steel microtubes and reference wires.

4. Discussion

This study investigated the feasibility of using the LREM on stainless-steel tube to produce a hollow preform. The LREM with and without argon gas filling were successfully performed on the microtube. Regarding the preforms fabricated with filled argon gas, it was observed that the excessive gas flow of over 170 cm^3/min determined the upper limit on generating complete preforms. The excessive gas flow provided a force on the bubble that exceeds the surface tension of melt, leading to the bursting of bubble and separation of the melt. Using a flow rate of 160 cm^3/min, it was expected that cavities would form within the preform, resulting in balloon-like structures. However, the small hemispherical voids formed at the interface of fusion and heat affected zone, as depicted in Fig. 2. If this is possible at materials with high surface tension and low density e.g. an aluminum alloy has to be investigated. Thus, achieving a stable hemispherical bubble in the melt and preform requires a delicate balance between the maximum gas pressure, surface tension of melt and the continuous escape of gas from the melt. In addition, the generation of hemispherical bubble was achieved at a gas flow rate of 160 cm^3/min rather than 80 cm^3/min, indicating that too low flow rate is not enough to generate a pressure to expand the bubble.

According to bubble pressure method (Rapp, 2017), the hemispherical bubble with a curvature diameter equaling to the capillary diameter experiences the highest possible pressure, before the bubble, in this case in the preform, detaches or gets destroyed. In addition, the continuous filling of gas results in the bubble expansion of the hemispherical void and ultimately bubble detachment from the capillary. Furthermore, it was observed that the hemispherical void already existed in the preform from 5 mm wire (see Fig. 2). With increasing melt wire length and corresponding filled gas amount, the size of the hemispherical void was generally unaffected (cf. Fig. 3).

Overall, the feasibility of the LREM of microtube has been successfully demonstrated. However, further investigations are needed to explore alternative approaches for generating a larger cavity in the preform.

5. Conclusions

This study investigated the feasibility of producing a hollow preform on the ends of stainless-steel microtubes using the laser rod end melting (LREM) and filling argon gas. It was shown that a hemispherical opened bubble can be generated at the end of the microtube by applying a gas flow rate of 160 cm^3/min. Thus, this study provides the initial evidence of the feasibility of using the LREM on microtubes for hemispherical void fabrication.

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References

Brüning, H., Jahn, M., Vollertsen, F., & Schmidt, A. (2016). Influence of laser beam absorption mechanism on eccentricity of preforms in laser rod end melting.

Brüning, H., & Vollertsen, F. (2015). Form filling behaviour of preforms generated by laser rod end melting. *CIRP Annals, 64*(1), 293–296.

Lu, Y., & Radel, T. (2022). Tensile strength of Nitinol flanges produced by laser rod end melting and immediate flange processing in a not fully solidified state. *Procedia CIRP, 111*, 721–725.

Rapp, B. E. (2017). Measuring Surface Tension and Free Surface Energy. In *Microfluidics: Modelling, Mechanics and Mathematics* (pp. 453–465). Elsevier.

Vollertsen, F., Friedrich, S., Kuhfuß, B., Maaß, P., Thomy, C., & Zoch, H.-W. (2020). *Cold Micro Metal Forming.* Cham: Springer International Publishing.

Zohuri, B. (2020). Different types of heat pipes. In *Functionality, Advancements and Industrial Applications of Heat Pipes* (pp. 183–238). Elsevier.