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Heat-affected zone analysis of fiber laser cut medical devices and its dependencies regarding laser and design parameters

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Abstract

Fiber laser cutting of Nitinol during the manufacturing of medical devices is very challenging due to many aspects. A change in the material's mechanical properties, caused by the local heating effects, is one these. Depending on the material's temperature during laser cutting, different types of microstructures can be observed: non-affected bulk material ($T_{Material} < T_{Recrystallization}$), heat-affected zone ($T_{Recrystallization} < T_{Material} < T_{Melting}$) and recast/dross ($T_{Material} > T_{Melting}$). The focus of this study is a quantitative investigation of the formation of these microstructures during fiber laser cutting. For this purpose, laser and process parameters (e.g. pulse duration, cutting speed, repetition rate, beam caustic) as well as geometric features of the specimen such as tip radius or strut width are varied to reveal their influence on the material during cutting.

Keywords: Micro-Cutting; Heat-Affected-Zone; Process Parameters; Microstructure

1. Introduction

In the manufacturing of medical devices, microstructuring is very often realized by laser cutting owing to its high accuracy and relatively low heat disposal. Two laser technologies are mainly used for this purpose, continuous wave (cw) - modulated fiber lasers and ultrashort pulsed (USP) lasers. The decision, which one to use, is a trade-off between the quality of the cutting surface, which is higher for USP lasers, and the cutting speed, where fiber lasers have their advantages. For tubes with relatively high wall thickness, e.g. for heart valve frames, cw-modulated fiber lasers are usually the preferred choice.

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During the fiber laser cutting process, the beam is focused via a lens and transmitted through a nozzle (see Fig. 1). The purpose of the nozzle is to concentrate the cutting gas onto the tube to prevent the cutting edge from oxidation and to blow out the molten material through the cutting kerf into the cooling water, which flows through the inside of the tube.

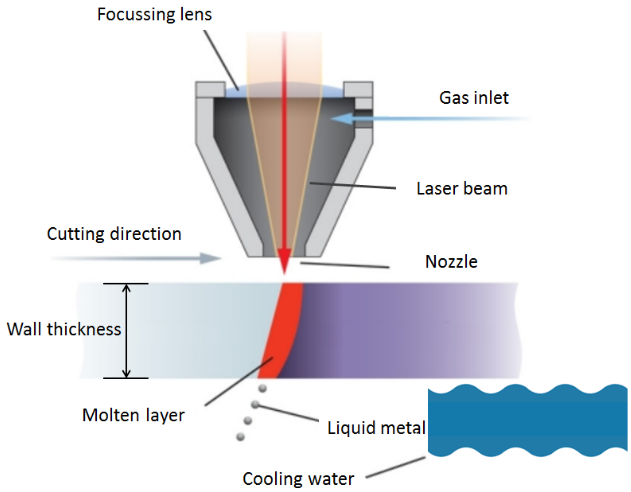
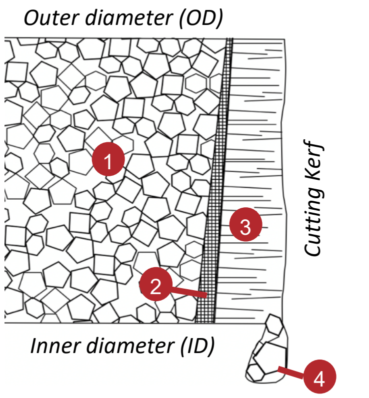
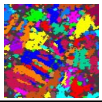
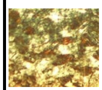
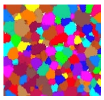
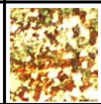
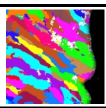
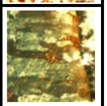
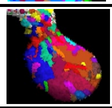
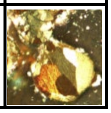


Fig. 1. Laser initiated fusion process.

Heart valve frames often require high wall thicknesses to fulfill the mechanical demands of the medical device. More laser power is needed and therefore a higher heat load is deposited, which makes the fiber laser cutting more challenging. If the temperature of the affected material exceeds certain values, its grain size is influenced. Table 1 summarizes the different types of material microstructures that can be identified after fiber laser cutting together with their grain orientation, size and representative images taken with electron beam scattering diffraction (EBSD) and color etching procedures.

Table 1. Overview of the different microstructures after fiber laser cutting (Braeuner, 2017)

Schematic View of Transverse Cross Section	ID	Name		Characteristic	Grains	EBSD	Color Etch
	1	BULK		Non-affected by laser process	Relatively large		
	2	LASER INFLUENCED AREAS	HAZ	Recrystallization Zone	Relatively small		
	3		RECAST	Resolidified Material	Oriented, columnar		
	4		DROSS	Resolidified Material	Not oriented, relatively large		

The non-effected BULK material has relatively large grains. Heat Affected Zone (HAZ) is the material which has been recrystallized, but was not molten, with comparatively small grains. RECAST is a molten and re-solidified surface layer on top of the cutting surface, characterized by oriented prolate columnar grain growth. DROSS consists also of re-solidified material with a drop-like shape formed at the inner cutting edge and is characterized by non-oriented grain growth with relatively large grains. The different grain sizes result in different material properties (Pelton, 2001), which is why their presence in medical devices should be avoided.

The goal of this study is to yield a better understanding of the physical dependencies of the process and design parameters regarding the appearance of HAZ on Nitinol tubes.

2. Set-up

2.1. Design of the specimens

A specific frame has been designed for the experiments with typical features from heart valve frames (see Fig. 2). The strut width and cut radius have been chosen to generate a finite area of HAZ when the process is run with nominal parameters.

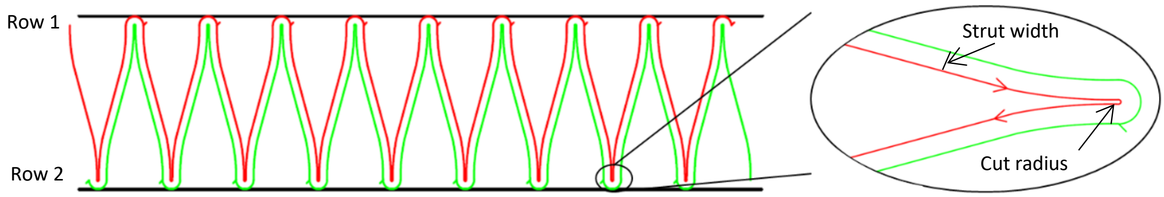


Fig. 2. Test design with a magnification of one tip end

The frame is composed of 2 rows with 9 tip ends, each. Owing to the narrow cut radius, where the laser beam makes a tight turn and returns on an outwards path close to the inwards path (see inset Fig. 2), these locations are defined as worst-case and are chosen for HAZ analysis. Hereby, row 1 and row 2 have to be considered separately, because their tip ends are cut subsequently. The green path is cut first. When the red path is cut in row 2, the air gap of the already cut green path acts physically as a heat barrier that could influence the thermal dynamics during the process.

2.2. Test plan and procedure

The frames are cut with a cw-modulated fiber laser, integrated in a self-built stent cutter. The pulses were nearly rectangular with certain peak power and pulse duration and emitted at an adjustable repetition rate. For the visualization of the grains via color etching or EBSD, the tip ends are embedded longitudinally in a cold mounting material then grinded and polished with sand paper from the OD towards the ID. After etching, the parts can be analyzed. A typical image of a color-etched tip end is shown in Fig. 3.

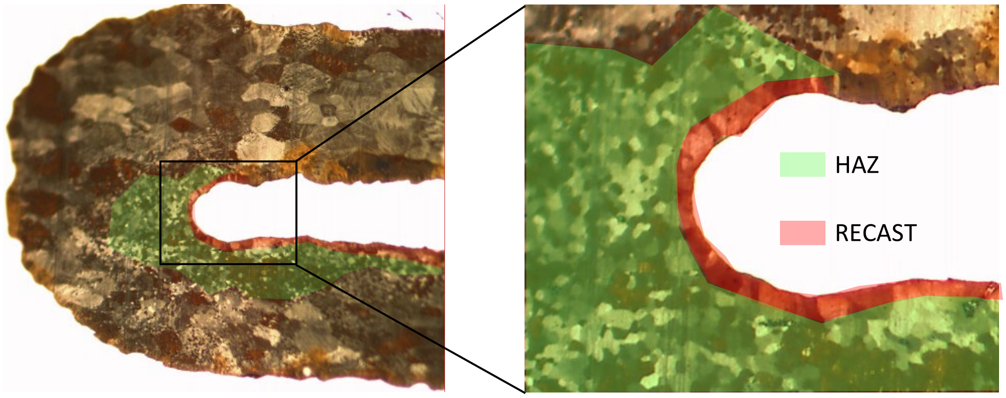


Fig. 3. Typical image of a color-etched tip end with magnification. HAZ and RECAST areas are highlighted in green and red, respectively

For purposes of comparing the different samples, the process output was defined as the area of HAZ measured in these images. The thickness of the RECAST layer does not change significantly with different process parameters and is usually removed in the manufacturing process of medical devices. Hence it is not considered. The shown HAZ area in Fig. 3 is approximately 21000 μm^2. Table 2 shows the list of input and output parameters.

Table 2. Input and output parameters of the study

Input parameter	*Output parameter*
Strut width	HAZ area
Cut radius	Minimum required laser power, P_{min}
Pulse duration	
Repetition rate	
Peak power	
Cutting speed	
Caustic of the laser beam	

The strut width and the cut radius have been varied as design parameters. Regarding the process parameters, the pulse duration τ_p, peak power P_{peak}, repetition rate ν_{rep}, cutting speed and the caustic of the laser beam have been changed. As output of the study, the described HAZ area is used. Furthermore, the minimum required laser power to cut the investigated tube, P_{min}, is introduced to compare different parameter settings and can be calculated with the above mentioned laser parameters.

$$P_{min} = \nu_{rep} * \tau_p * P_{peak} \tag{1}$$

3. Results

3.1. Process characterization

The process and measurement methodology were characterized and its repeatability tested prior executing this study, which led to three findings. To explain these findings, the EBSD image in Fig. 4 is used, which shows the last fraction of the wall of the tube close to the ID.

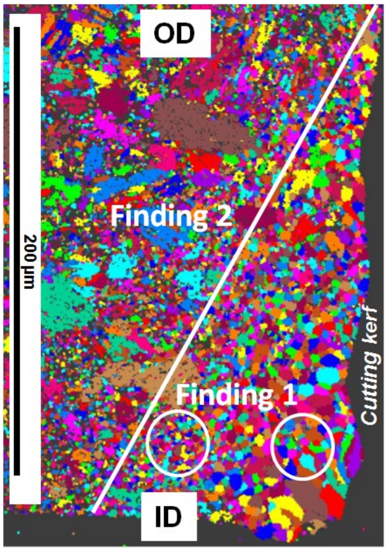


Fig. 4. EBSD measurement from OD to ID to support the theory of significant more HAZ occurring at the ID

First, the grain sizes of the HAZ are dependent on the distance to the cutting kerf, which is indicated as Finding 1 in Fig. 4. The probable reason for this phenomenon is the different temperatures at the different material depths during the process.

Second, a strong variation in the HAZ area between the nine tip ends from row 2 could be detected. One reason for this is the dependency of measured HAZ on the plane of analysis. The HAZ area is bigger closer to the ID (Fig. 4, Finding 2), attributed to the longer interaction time of the bulk with the molten material. A tool to measure the depth of grinding has been developed and was used in this study. Dependent on that value, the HAZ at the ID has been calculated based on a linear model (see white line in Fig. 4) and was chosen as output of the study.

Third, row 1 and row 2 showed very different HAZ responses, which can be explained by the different cutting sequence described in section 2.1. The limited heat capacity due to the relatively small volume at the tip end is responsible for HAZ and not the tight cutting radius. As a consequence, only the nine tip ends from row 2 were used for assessing the parameter variation.

To check the repeatability of the system regarding HAZ, four samples with nine tip ends, all processed identically, were analyzed (Table 3).

Table 3. Characterization of the process stability

	HAZ area [1000 µm^2]	Standard deviation [1000 µm^2]
Sample 1	36	7
Sample 2	32	8
Sample 3	29	13
Sample 4	31	19
	32	11,75 (~30%)

The standard deviation for the HAZ area is still relatively high and must be considered in evaluating the significance of the achieved results.

3.2. Parameter variation

The design parameters were varied first. The results regarding the strut width are shown in Fig. 5.

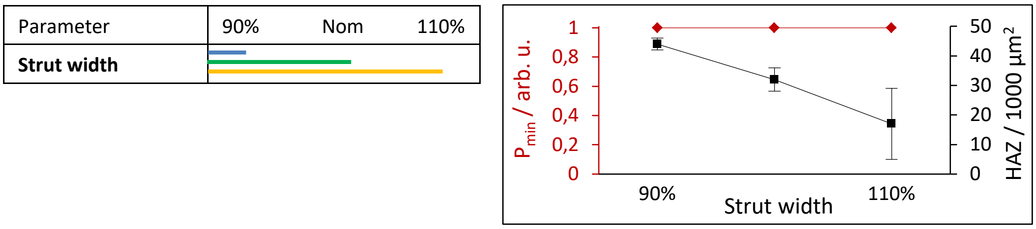


Fig. 5. HAZ – Variation of the strut width

The left side of the figure shows all input parameters with the varied one is indicated in each case in bold. For the shown test case, only the strut width has been changed and all other parameters have been kept constant. The colored bars indicate how many parameter sets have been tested. The strut width changed between 90% and 110%. The minimum required laser power is constant and the bigger the struts, the smaller the HAZ. It is highlighted here, that the formation of HAZ is very sensitive in regards to strut width. A change of 20%, being approximately 40% in volume at the tip end, resulted in an almost 300% bigger HAZ area. The standard deviation within the nine tip ends for each measurement point has also been included.

Fig. 6 shows the results from varying the cut radius between 100% and 200%.

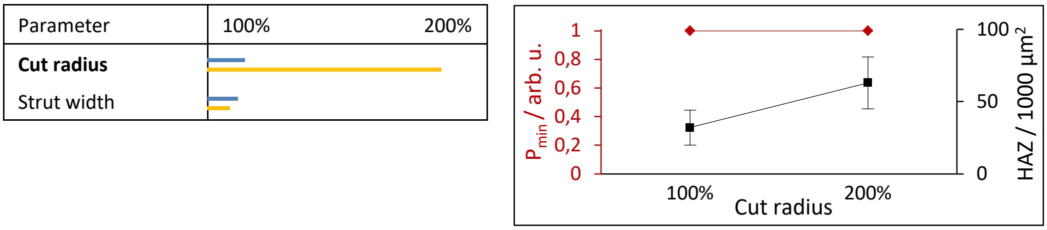


Fig. 6: HAZ – Variation of the cut radius

If the cut radius is changed, also the strut width is impacted, which is indicated in the table. The minimum required power is constant. HAZ increased with increasing cut radius, which again demonstrates that for the investigated test design, the limited volume of the strut is contributing to the formation of the HAZ and not the tight cut radius which would otherwise be expected to decrease the HAZ area.

The results for different pulse durations are shown in Fig. 7. For the variation of the laser parameters, all other relevant parameters are listed together with the resulting average power.

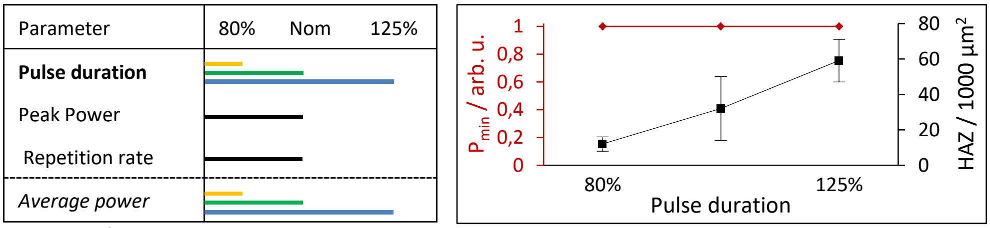


Fig. 7: HAZ – Variation of the pulse duration

The pulse duration, and also the average laser power, has been changed between 80% and 125%. The minimum required laser power corresponds to a pulse duration of around 70%. The HAZ area increased with pulse duration and average power.

Fig. 8, right, shows the results regarding peak power. To achieve the same average power for all tests, the pulse duration has been adapted.

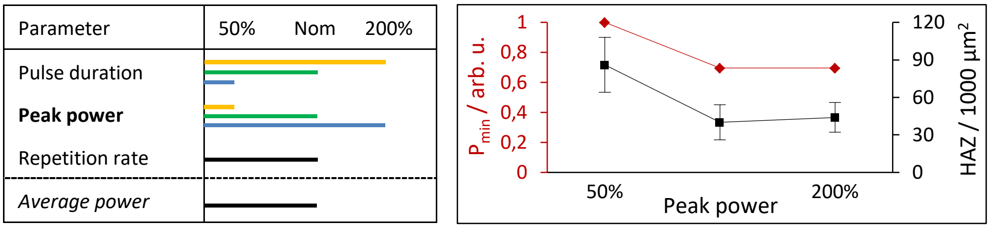


Fig. 8. HAZ – Variation of the peak power

The minimum required laser power and HAZ decrease if the peak power increases. This means for higher peak power levels, the process requires less laser power. The reason could be that for longer pulses and lower peak power, the heat can diffuse more efficiently into the adjacent material and therefore, more laser power is required. It seems a further increase in peak power does not decrease the extent of HAZ any further for the investigated tube dimensions.

Fig. 9 summarizes the results for the variation of the repetition rate. In this experiment, also the pulse duration and average power varied.

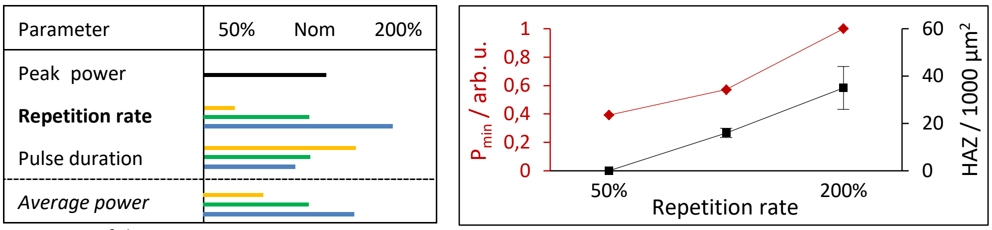


Fig. 9. HAZ – Variation of the repetition rate

If the repetition rate is increased, the process requires a much higher average power. Also the HAZ area is larger for higher repetition rates. The reason for this actuality is probably different thermal dynamics.

Fig. 10 displays the results for different cutting speeds. All other input parameters were held constant.

Parameter	25% Nom 200%
Cutting speed	

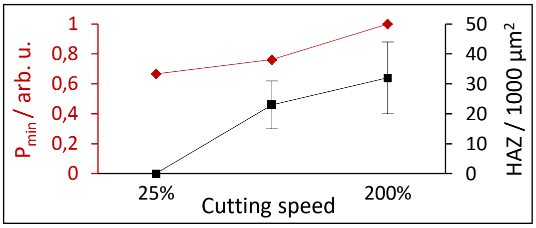


Fig. 10. HAZ – Variation of the cutting speed

The minimum required laser power is lower for lower cutting speed. This is deemed due to a higher pulse-to-pulse overlap resulting in a smaller volume that each pulse has to fuse. The HAZ area decreased with lower cutting speed even though the energy input per unit length is higher. A reasonable explanation is superior cooling by the processing gas and a better efficiency of blowing out the molten material.

The different beam caustic settings are realized by expanding the beam before entering the focusing lens with a fixed focal length. The different settings are shown in Fig. 11.

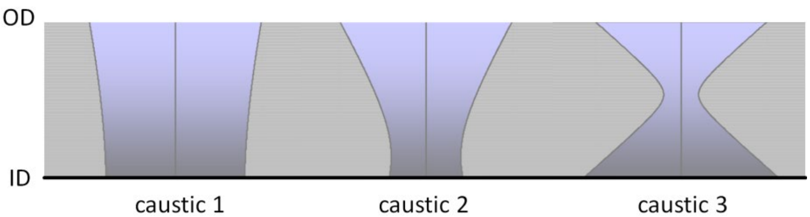


Fig. 11. Picture of the different beam caustic adjustments

The results regarding the caustic are shown in Fig. 12.

Parameter	Nom
Beam caustic	

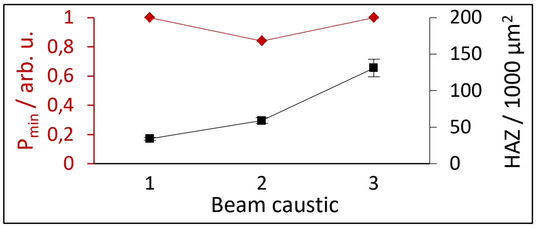


Fig. 12. HAZ – Variation of the caustic of the laser beam

The minimum required laser power varied only slightly among the different settings. The HAZ increased clearly with the divergence of the beam.

4. Conclusion

In this study, different laser and process parameters were changed and their influence on the occurrence of HAZ was analyzed. In addition, the minimum required laser power for cutting the investigated tubes has been examined.

It was determined that the cutting strategy plays an enormous role regarding the formation of HAZ meaning that the sequence of the different cut paths can influence the occurrence of HAZ. Furthermore, the variance of the area of HAZ is relatively high for given parameter sets. The reason could be location-dependent material properties due to the tube drawing process of Nitinol. For the process and design parameter variation, one outcome was that HAZ is very sensitive regarding the strut width. It can be concluded that lower pulse duration, higher peak power and lower repetition rate decreased the area of HAZ.

For future investigations, different tube dimensions have to be investigated. In this study, only one type of tube has been used. With that information, the probability of HAZ occurrence for a specific design can be addressed very early in the development phase. In addition, a process simulation to predict a detailed behavior of the material temperature during fiber laser cutting should be realized.

From an application stand-point, the HAZ with different grain sizes needs to be characterized in terms of mechanical properties. This can further lead to an evaluation how the functionality of a medical device is affected if HAZ is formed during fiber laser cutting.

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