Lasers in Manufacturing Conference 2017

Swift and accurate - investigation of remote laser cutting for open cell foams

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Abstract

It is well known that the global climate change is the largest challenge for the society of the 21th century. For managing the resulting consequences, innovative materials become more and more important for energy efficient applications. Open cell metal foam contributes promising solutions to the light weight design, battery applications and renewable energy harvesting. Still, challenges are present concerning the cutting into a defined shape. The remote laser cutting offers a solution for decreasing the production costs as well as the needed component accuracy. Our investigations consider that this technique has a high potential concerning cutting speed, which was increased more than 500% compared to state of the art laser separation. Next to that, the contour accuracy was improved as well, resulting in tolerances with less than 60 µm. This paper offers insight into the viability of remote laser cutting in overcoming the challenges dealing with mechanical milling or grinding. Investigating the process concerning thermal stress input as well as particle attachments will be the next steps in the future.

Keywords: cutting; laser; accuracy; metal foam; Inconel;

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1. Introduction

For overcoming the upcoming challenges of the global climate change, innovative material like open cell metal foams deliver promising solutions in the field of light weight design and energy efficient applications (heat exchangers, battery systems) [1] [2] [3]. Nevertheless, those solutions have to be affordable. Cost reduction is increasingly becoming a vital factor in production processes. Different opportunities had to be explored, in order to fulfill the demand to a higher rate of flexibility compared with large scale production. Note that traditional mechanical processes like milling or grinding were investigated in order to close this gap [4]. Nevertheless, the disadvantages like tool costs and tool wear still limit the potential. In addition, milling modifies the surface property resulting in a smearing effect. Moreover, this concludes in a loss of the cellular structure. Current solutions to increase the production speed are unsatisfactory. Mechanical processes deliver cutting speeds, which are not high enough for large scale production [4] [5].

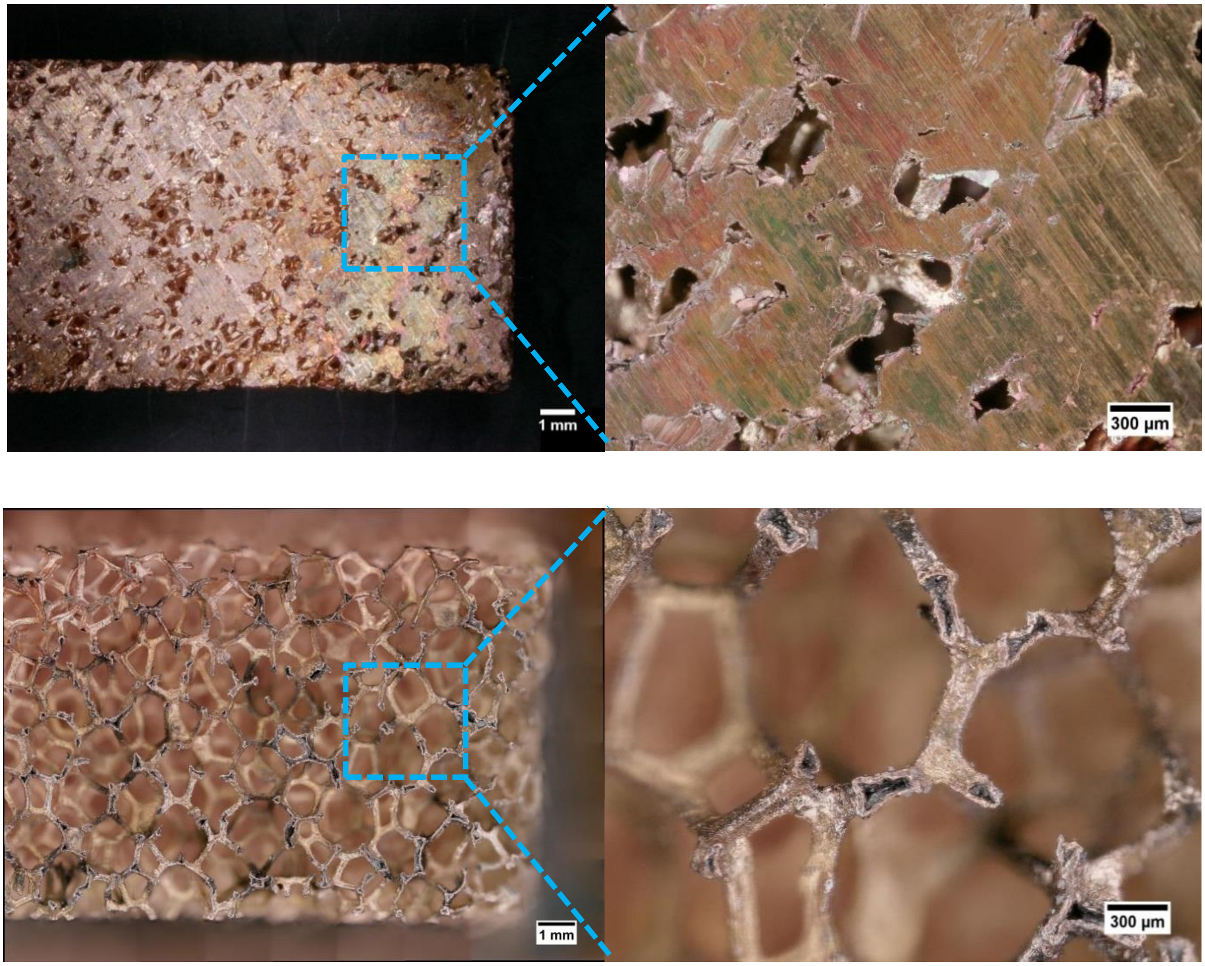


Fig. 1. Microscopic investigation of the smearing effect: metal foam before (left) and after mechanical machining (right); loss of cellular behavior through surface defects

In contrary, laser technology is a new approach for cutting metal foam due to the fact that it is a wear-free and highly flexible process [6]. Several experiments were carried out using the laser fusion cutting technology [7]. Furthermore, this is an established separation technique in various fields of industrial applications. The basic principle is well known as the laser beam is absorbed at the surface of the material and melts the entire bulk at once. A coaxial high pressure gas stream (for example N2, Ar, or air) ejects the molten material to the bottom side of the specimen [6]. Due to melting the entire bulk in the cut kerf at once, a thermal stress is induced. Consequently, several investigations are dealing with induced thermal stress into the foam material in order to determine and evaluate the cutting parameters as well as the geometry of the contour [8] [9]. Additionally, the property of the open cell structure decreases the combustion of the process gas. Nevertheless, dross attachments as well as thermal stress are the biggest challenges that have to be investigated in more detail.

Remote cutting is a promising approach in sizing with laser [10]. Moreover, it has the possibility to reduce the thermal induced stress. Furthermore, the open cell structure will be kept as well as the preferred contour outline [11]. The investigation verifies the novel remote laser cutting technique for open cell foams. Relevant core themes of the research are the achievable separation velocity, edge geometry and achievable component tolerances. The second section will give an introduction into the experimental setup. Explaining the basic principle of remote laser cutting as well as the methodology are the major subjects in the section. A special focus is set on the imaging process and how it can be used for getting reliable results. Consequently, the third section focusses on the material characterization and the cutting process parameters. Finally, the fourth section illustrates the results regarding the four major core themes

2. Experimental setup

Since the basic physical principle is not well known, this section will describe the remote laser cutting in more detail. The laser beam is absorbed at the surface and melts only a small volume of the irradiated area. Next to the molten part, a certain kind of material is vaporized. This vapor is called steam cavity and consists of a high amount of pressure, which ejects the molten material. For achieving the steam cavity in the cut kerf, a high intensity of the laser beam is required. It is known that this could be achieved by using small spot sizes in the focal plane. The cut kerf is created in a gradual ablation. Moreover, the melt and vapor is ejected to the top side of the specimen. Consequently, small spot sizes ($Ø_{spot}$ < 100 µm) at large working distances require a high beam parameter product (BBP). Accordingly, a single mode fiber laser was utilized for the following investigations [6] [12] [10] [11].

The word “remote” in the meaning of laser cutting describes the beam manipulation system, which focuses and deflects the laser radiation. Hence, the beam gets deflected by mirrors, which are attached on highly dynamic galvanometric drives. Typically, a larger distance (up to 650 mm) to the material surface is adjusted compared with other laser cutting technologies (0.5 mm – 1.5 mm). Summarizing the different separations techniques, the basic principle of the remote laser cutting and fusion cutting is illustrated in Figure 2. Bulleted lists may be included and should look like this:

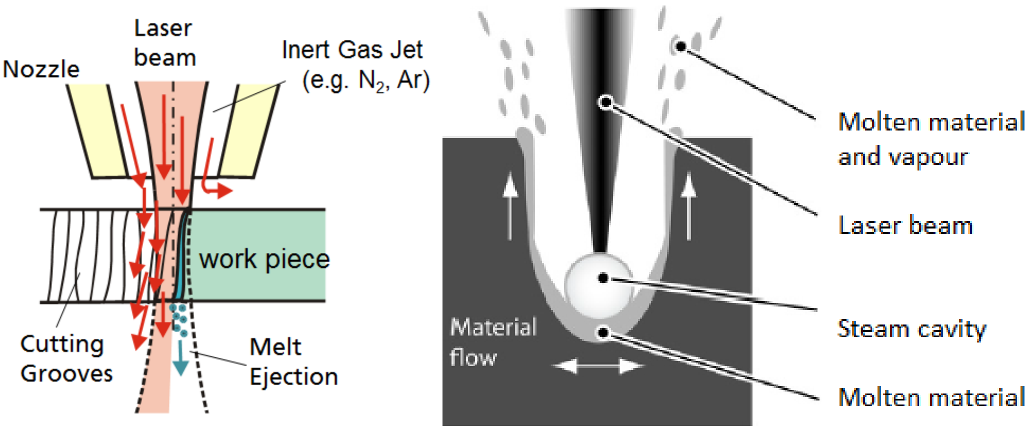


Fig. 2. Theoretical work principle of laser fusion (left) and laser remote (right) cutting

Laser remote cutting as an alternative separation technique for metal foams will be discussed in terms of four main criteria; achievable cutting speed, edge shape, thermal damaging and oxygen distribution. Due to the fact that the laser beam is deflected by mirrors, cutting speeds of up to 1·200 m/min are possible. Furthermore, stepwise ablation of the material during remote cutting offers an opportunity to manipulate specific process parameter (laser power, idle time between cycles, cross jet pressure, scan velocity). Moreover, optimizing these can reduce the thermal damage zone [11].

As mentioned, for the remote laser cutting technique high brilliant beam sources are indispensable. For the following investigations, a single mode fiber laser with a maximum output power of 5·000 W is utilized. Due to the fact that the beam size has a significant influence to the spot size, a collimator with a focal length of 200 mm is used [13]. As a beam manipulation system a scanner with an aperture of 20 mm and two different focal lenses (340 mm and 500 mm focal length) were considered. The results of the optical components are measured with a laser beam diagnostic system and shows spot diameters of 61 µm (f340 mm) and 86 µm (f500 mm).

In this report, open cell foam out of Inconel 625 was investigated. Table 1 present the most important material parameters.

Table 1. Material parameters

Thickness (mm)	Pore size (mm)
1.6	0.45
1.9	0.58
2.7	0.80
3.1	1.200

For determining the possible cutting speed, the results had to be categorized into three different groups. All samples were analyzed via microscopy and defined as “cut”, “nearly cut” and “no cut”. A sample, which is located in the “cut” category possess a complete and clear kerf without any struts, as illustrated in Figure 3 left. While a “nearly cut” contains some remaining struts and a “no cut” shows multiple incomplete sections in the kerf (Figure 3). Moreover, with this cut categorization the possibility to determine the cutting velocity for both setups and foams are given.

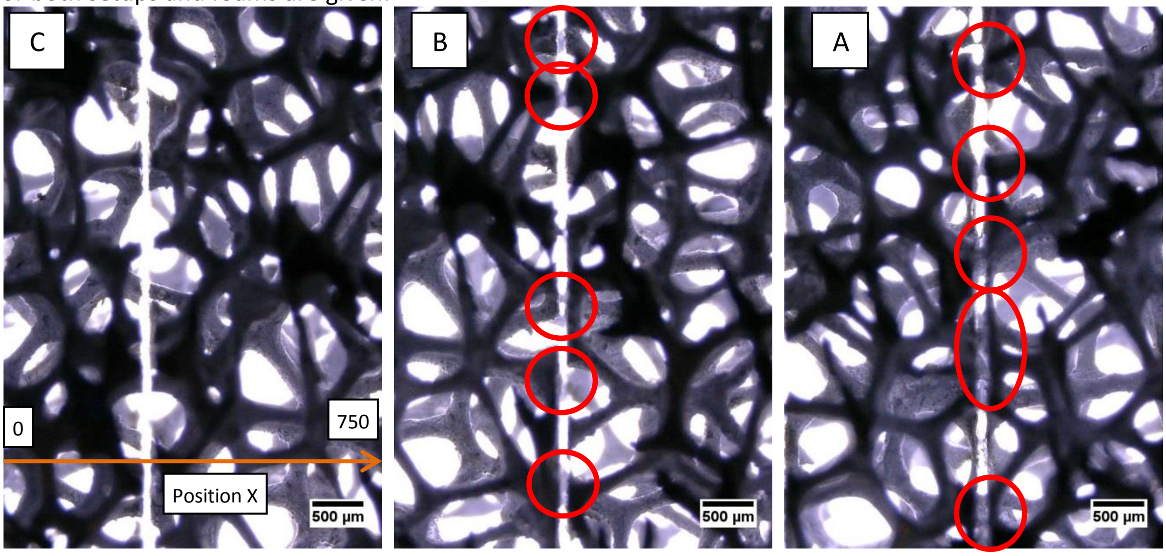


Fig. 3. Optical analyzed samples and classification into the different cut categories, "no cut" is displayed on the right, "nearly cut" is illustrated in the middle and "cut" is presented at the left image

First of all, an image of the surface as in **Fehler! Verweisquelle konnte nicht gefunden werden.** of the sample was taken and segmented into vertical lines. Consequently, the background of the images was white, which represent a grey value of 255. The average grey value of these vertical lines ($0 < I_{gv} < 255$) were calculated and recorded. If a grey value is above the 250, the sample was set into the “cut” category. A grey value between 230 and 250 represent the “nearly cut”. All remaining results can be seen as a “no cut”. This process is exhibit in **Fehler! Verweisquelle konnte nicht gefunden werden.**.

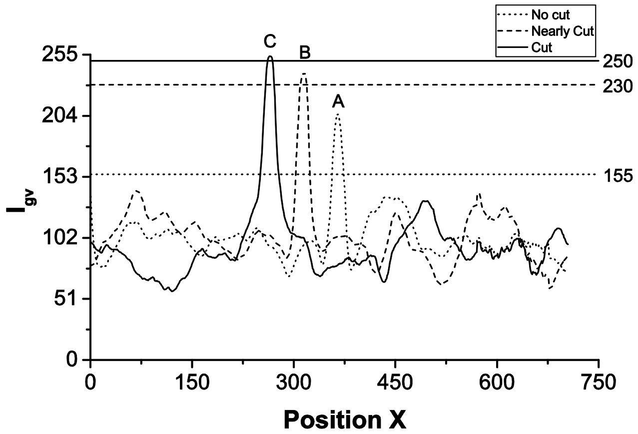


Fig. 4. Classification into different cut categories

Concerning the determination of tolerance, all data were taken by standardized and gauged measuring machine. This machine has the opportunity to gather the data ductile and optical. In this case the measurements were taken with an optical tool.

3. Results

For determining the cutting speed, the fluence was linearly raised and the numbers of scan cycles were adapted to achieve a complete cut, respectively. In conclusion, a correlation between cutting speed and fluence is illustrated in Figure 5.

$$F_{lz} = \frac{4 \cdot P}{\pi \cdot d_f^2 \cdot v_s} \left(\frac{J}{m^2} \right) \quad (1)$$

P... Laser power (W), d_f... beam diameter in focal plane (m), v_s... scan velocity (m/s)

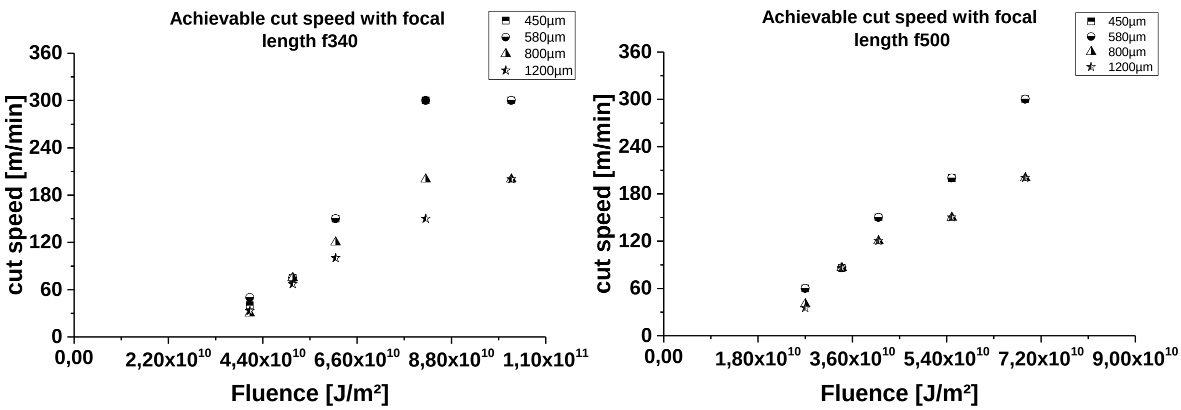


Fig. 5. Achievable cutting speed of Inconel foam depending of the focal length, chosen focal length achieves diverse spot diameter and consequently different intensities

The setup indicates for the investigated material thicknesses a nearly linear rising of the achievable cutting speed as it can be seen in Figure 5. With higher laser intensities, more cell struts are cut in one cycle. Therefore, a complete cut is achieved with fewer cycles, which leads to higher cutting speed. Lower intensities demand more cycles, which lead to an unfavorable heat up of the cutting edge. Both setups can reach a cutting velocity up to 300m/min even with different intensities. This effect is influenced by the laser power and interaction time between the material and the beam. Both setups operated with the same scan velocity but beam diameter differs, which lead to a higher energy input over the time with larger beam width.

Table 2. Determination of the different interaction times

Setup	Focal length	Spot diameter	Scan velocity	Interaction time
1	340	56	10	5,6
2	500	86	10	8,6

A geometrical aspect of the cut area has to be investigated as well. As mentioned, state of the art separation techniques like milling, grinding or punching are creating a disorientation of the edge. Especially punching influence the edge geometry due to a squeezing effect. Exemplarily, the determination of the degree of utilization is depicted in Table 3. As it can be seen in Table 2 the interaction time of setup 2 is ~50% higher than in setup 1. This assumes that 50% more energy is getting into the material over time. This could explain why with lower intensities it is possible to reach the same cutting speed.

Next to the achievable cutting speed the cut kerf delivers an important impact, because with this classification number the minimal achievable geometry is determined. Therefore, the importance on a process development is given.

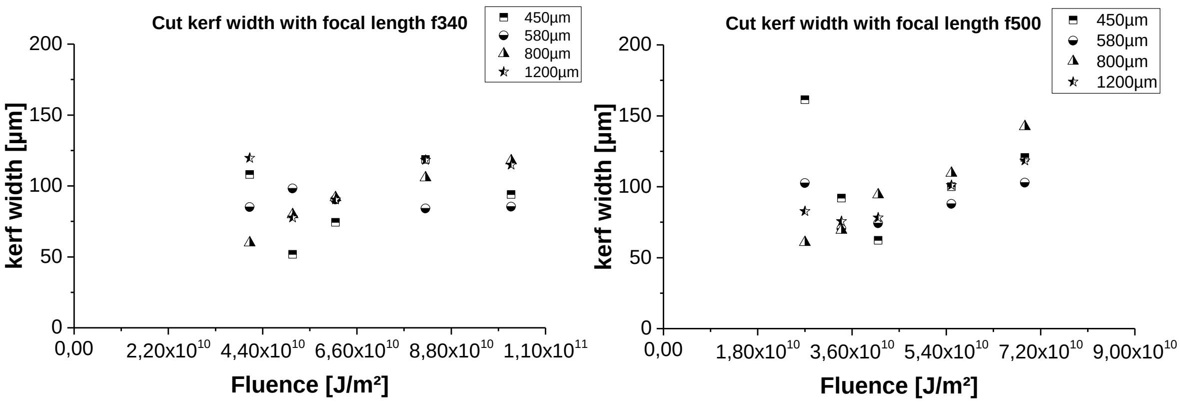
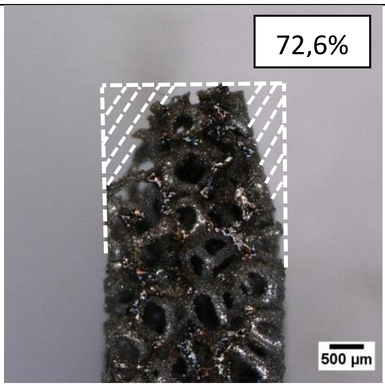
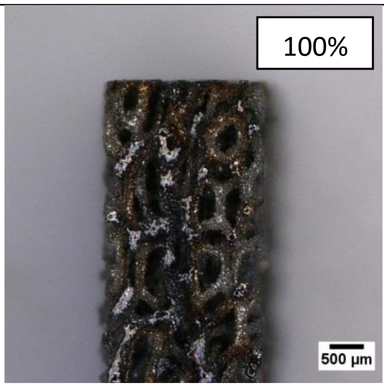


Fig. 6. Determination of cut kerf width

To determine the cut kerf width is the first step in order to define the achievable cutting tolerances. As it can be seen in Figure 6 the kerf width varied over different intensities. This effect can be explained with the achievable cutting speeds. Note that less intensity require more cutting cycles for the complete cut. Therefore, the laser beam heat up the cutting edges, which causes a large thermal effect zone. This effect zone absorbs more laser radiation so that the kerf width is increasing.

A geometrical aspect of the cut area has to be investigated as well. As mentioned, state of the art separation techniques like milling, grinding or punching are creating a disorientation of the edge. Especially punching influence the edge geometry due to a squeezing effect. Exemplarily, the determination of the degree of utilization is depicted in Fehler! Verweisquelle konnte nicht gefunden werden.

Table 3. Measurement example for the degree of utilization of Inconel foam, Pore size 1200µm

Pore size	Mechanical cut	Laser cut
1200µm		

As demonstrated in Table 2 the hatched area represents the amount of material which is lost. In conclusion, only 72,6% of the material at the edge is operative for the designed purpose. Note that the material is getting squeezed into the remaining foam structure which influences the pore size and distribution. In comparison, laser cutting shows no edge deformation or squeezing. For all different pore sizes the remaining material at the edge was calculated and illustrated in Table 4. As it can be seen, the degree of utilization for remote laser separated foam is always at 100% whereas the mechanical cut creates values between 82% and 72%. This 100% degree of utilization could be explained by the forceless separation with laser beams. Note that with increasing pore size the material thickness is getting larger due to fabrication aspects [2]. A larger pore size and foam thickness leads to a greater area, which is effected by the cutting force. That is why an increase of the pore size leads to a decrease of the degree of utilization.

Table 4. Achievable degree of utilization

Pore size	Mechanical cut	Laser cut
450µm	82,1%	100%
580µm	73,3%	100%
800µm	73,4%	100%
1200µm	72,6%	100%

For determining the achievable contour accuracy, a circle specimen was cut with a programmed diameter of 15 mm. A cut kerf correction was not executed, which leads to a smaller measured diameter of the circle. For each porosity and their correspond thickness, ten circles were manufactured. Each measured circle consists out of 20000 data points. In Table 5 the results of every sample is illustrated.

Table 5. Measured samples for determination of accuracy

Pore size	450µm	580µm	800µm	1200µm
Average	14,9035mm	14,9081mm	14,9161mm	14,8877mm
Standard deviation	0,0102mm	0,0076mm	0,0138mm	0,0183mm

It can be seen that the average of these specimen is always around 100 µm smaller than programmed. This could be compensated with a cut kerf correction, based on the cut kerf measurements, which were presented above. More important is the standard deviation of the samples, because it represents the real achievable tolerance. As it can be seen, component accuracies from ±7µm to ±18µm are possible.

4. Conclusion

Summarized, the remote laser cutting offers solutions for upcoming challenges concerning shaping of open cell metal foam. An achievable cutting speed from up to 300 m/min is possible, which is an increase to state of the art separation techniques of more than 500 %. Note that with larger pore size the material thickness increased respectively, which concludes in a lower separation velocity. Next to the cutting speeds the results shows perfect perpendicular edge geometry. This leads to tolerances from less than ±20µm, for some pore sizes ±7µm are reachable. Further investigations will consider an increase of material thickness as well as slicing the foam into thin components.

Acknowledgements

The authors gratefully acknowledge support and funding from the German ministry of research and development (BMBF) grant no. 03X4637A-H

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