Non-thermal Laser Forming of Sheet Metal*

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Abstract

In this paper the results of some preliminary experiments are presented on non-thermal microforming of thin metal sheets with laser induced optical breakdown shock waves. Three sheet metal forming processes are realized with this method. The most deeply investigated process is laser stretch-forming, since the influence of parameters like defocussing, power density, pulse energy, number of pulses, and material could be worked out. The results show that uniform shaped domes with a dome height over 250 µm with diameters of 1.4 mm could be produced. Additionally, first investigations on laser stamping and laser embossing have been carried out, but are not presented in this paper.

Keywords:

Laser forming, Sheet metal forming, Stretch-forming

1 Introduction

Laser forming of sheet metal is well known as a process where different thermal mechanisms cause a bending of the sheet metal [1]. The most commonly known thermal mechanism is the temperature gradient, which causes inhomogeneous strains within the material, which results in an incremental forming process. In contrast to this process, non-thermal laser forming is a fairly new process, which does not use thermal mechanisms, but the optical low-threshold surface breakdown [2,3], which results in the creation of a shock wave. Its principle was first shown by O'Keefe [4]. He used a Q-switch Nd:YAG-Laser with a maximum power density of 1.7 GW/cm². The experiments showed thermal and mechanical damaging, but were not used for deeper investigations on sheet metal forming processes.

The shock wave is the responsible energy source for this forming process. This means that the forming velocity is mainly driven through the velocity of the shock wave.

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[*] *This work has been funded by the Leibniz-award Vo 530/7-1; the authors would like to thank the Deutsche Forschungsgemeinschaft for their financial support*

The forming behaviour can hence be compared to the one of a high speed forming process like electromagnetic forming or explosive forming. The whole process duration cannot be assessed yet, but it is probably longer than the laser pulse duration of 20 ns, since the plasma formation, shock wave propagation, and bending processes occur successively.

The laser induced shock wave can in principle be used for all sheet metal forming processes, as long as the parts are in micro- or mesoscopic range. The following investigations are in non-thermal laser stretch-forming.

2 Method

Laser induced shock waves are well known and can be applied on metals by pulsed excimer laser beams through very high energy densities and are currently used for shock hardening. Figure 1 shows different laser surface treatments by excimer laser versus energy density, whereby the shock hardening requires the highest energy density, even higher than the energy density for ablation. This indicates that shock hardening is always accompanied by ablation. But ablation can be reduced by confined plasma through a transparent facing like transparent plastics or fluids like water. An interesting side effect of such facings is the increase of pressure of the shock wave on the target [5].

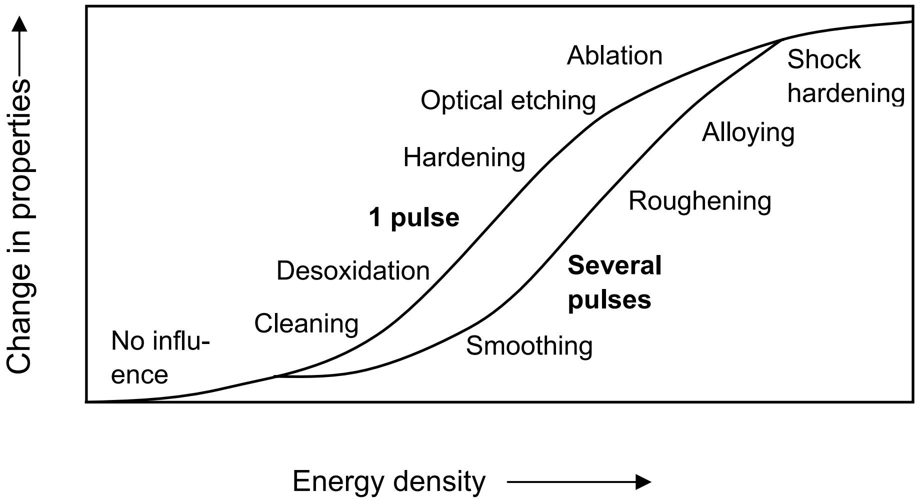


Figure 1: *Surface treatment of metals by excimer lasers [5]*

This preliminary knowledge about shock hardening was the basis for the test setup for non-thermal laser induced stretch-forming experiments, see Figure 2. The sheet metal is wet by a water film of several millimetres in height in order to generate a confined plasma and than placed on a circular die and clamped by a blank holder. In a next step one short laser pulse hits the sheet metal and causes ablation at the surface of the sheet, accompanied by a plasma pulse. As a counter-reaction of the plasma formation a shock wave occurs and causes the stretch-forming of the sheet.

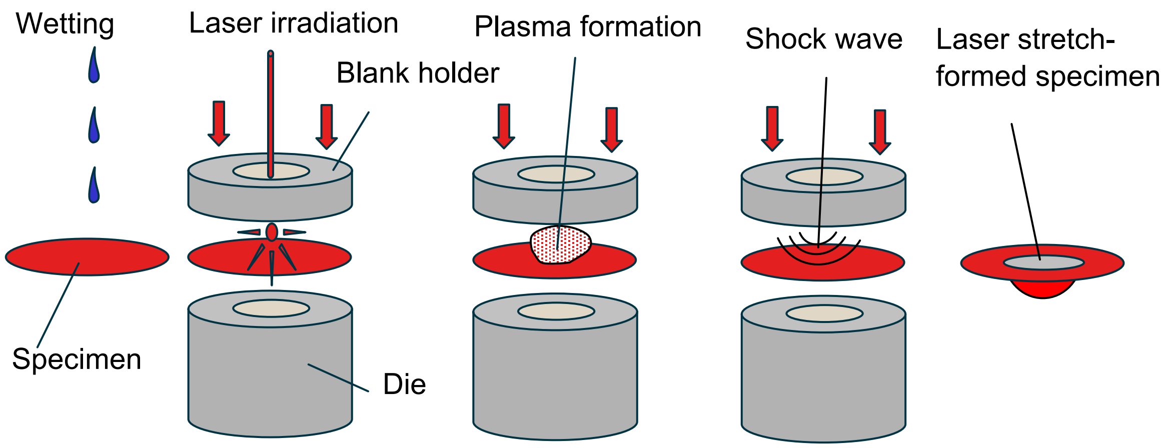


***Figure 2:** Schematical process of non-thermal laser stretch-forming*

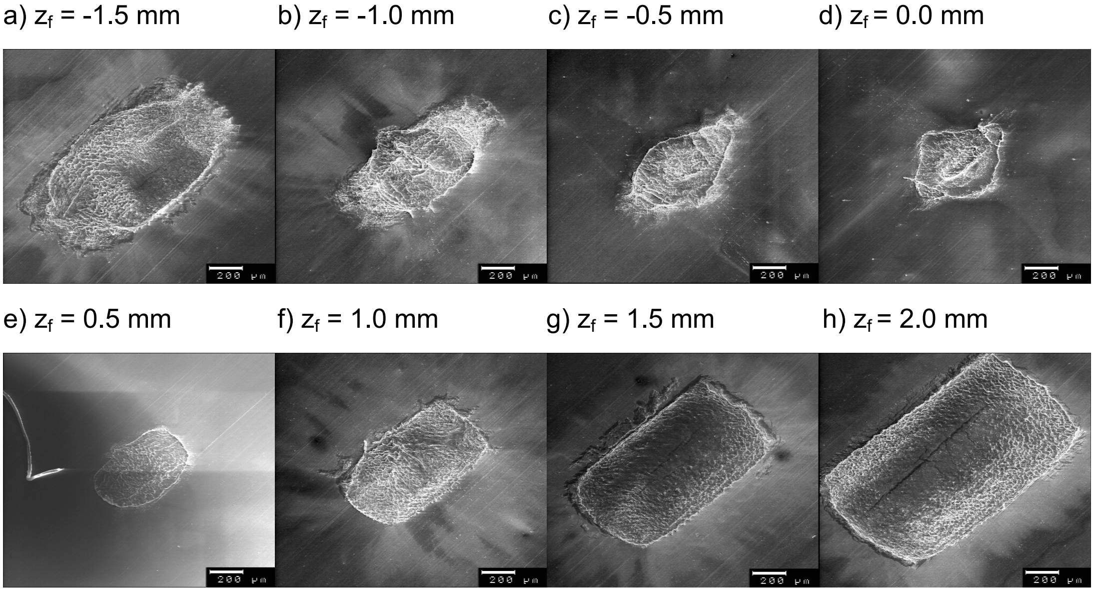
3 Experimental results

Several laser induced stretch-forming experiments were carried out, while changing parameters, such as defocussing, water height, number of pulses, pulse energy, material, and diameter of the die. The used excimer laser has a wave length of 248 nm and a pulse duration of 20 ns. The maximum pulse energy is 250 mJ and the maximum power density is 6.4 GW/cm², whereby a power density of 0.1 GW/cm² is sufficient to ignite a plasma [6].The dome height of the laser stretch-formed parts can be seen as a degree for the forming, as long as a uniform dome is formed.

3.1 Influence of defocussing and water film

The defocussing z_f is defined as distance between work piece and focus of the laser beam, whereby z_f is positive if the focus is above the work piece, and negative if the focus is within the work piece. The highest energy density is thus at a defocussing of zero. The maximum applied stress of the shock wave will then also be found at a defocussing of zero.

Single laser shots on an aluminium foil of 50 µm in thickness were carried out with different defocussings with and without a water film. Figure 3 shows the size of the spot while changing the defocussing from -1.5 mm to +2.0 mm. It can bee seen that significant ablation takes place in the focus. In comparison to this, the same experiments were carried out with a water film of 2 mm height, see Figure 4. The smallest spot area is at a defocussing of +1 mm, which means that the focus is shifted by 1 mm towards the work piece. This is due to the fact that the laser light is diffracted at the transition point from air to water, since the refraction index for water is higher than for air. The ablation is significantly less compared to the experiments without water film.

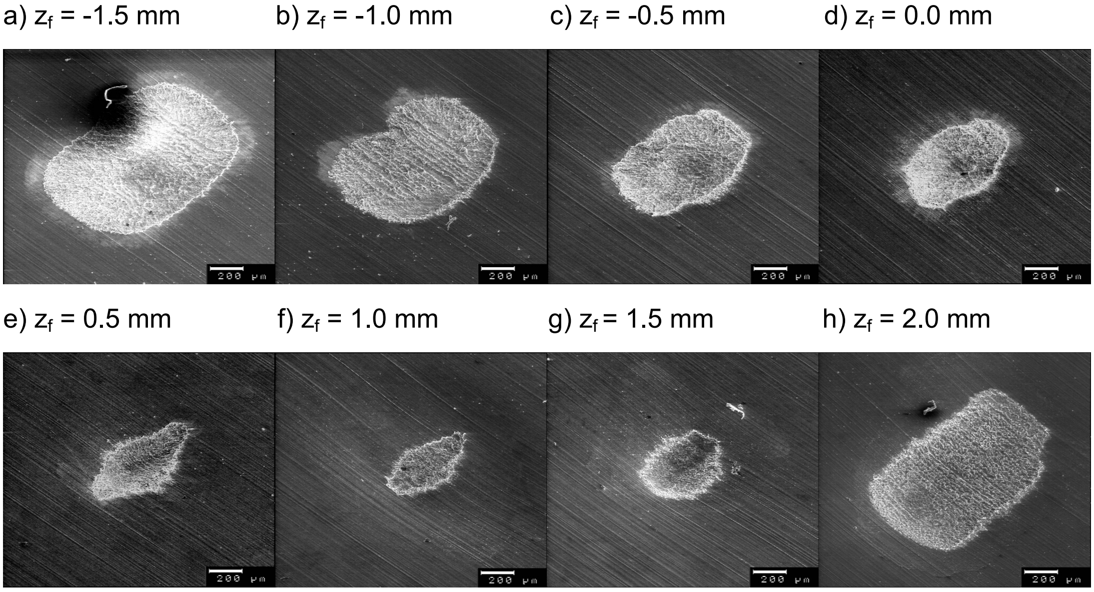


a) z_f = -1.5 mm b) z_f = -1.0 mm c) z_f = -0.5 mm d) z_f = 0.0 mm

e) z_f = 0.5 mm f) z_f = 1.0 mm g) z_f = 1.5 mm h) z_f = 2.0 mm

***Figure 3:** Laser spot on 50 µm Aluminium foil, without water film, wave length 248 nm, puls duration 20 ns, puls energy 250 mJ, power density 6.4 GW/cm², variation of the defocussing z_f in steps of 0.5 mm from a) to h)*

The highest dome height of laser stretch-formed parts without the use of a water film can be reached in the focus where the average dome height is 225 µm, see Figure 5. The dome height of other experiments with a defocussing of +0.5 till +1.5 mm was significantly lower. It has to be said that the parts which were formed in the focus without a water film did not constitute a uniform shape, but a peak similar to the example in Figure 7b), so that these parts are scrap.



a) z_f = -1.5 mm b) z_f = -1.0 mm c) z_f = -0.5 mm d) z_f = 0.0 mm

e) z_f = 0.5 mm f) z_f = 1.0 mm g) z_f = 1.5 mm h) z_f = 2.0 mm

***Figure 4:** Laser spot on 50 µm Aluminium foil, water film height 2 mm, wave length 248 nm, puls duration 20 ns, puls energy 250 mJ, power density 6.4 GW/cm², variation of the defocussing z_f in steps of 0.5 mm from a) to h)*

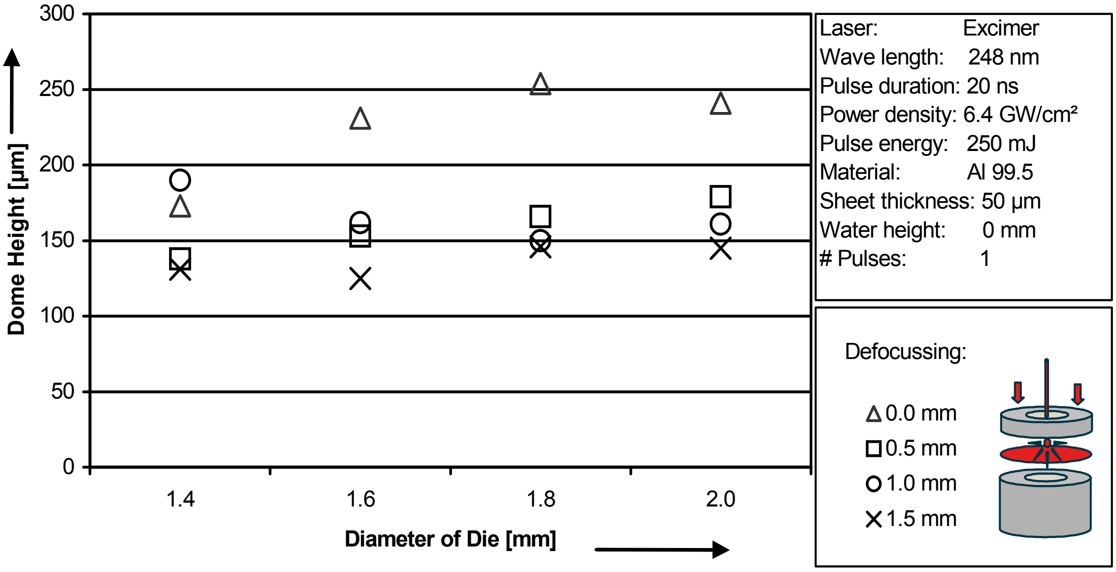


***Figure 5:** Dome height of laser stretch-formed parts depending on the defocussing (no water film)*

The same experiments under the use of a 2 mm water film procued not only consistently uniform shaped parts, but also an average dome height of 256 µm at a defocussing of +0.5 mm, see Figure 6. Experiments with other defocussings resulted in lower dome heights, which means that the best working point under the use of a water film has been shifted from the focus to a defocussing of +0.5 mm (not taking into account the diffraction through the water).

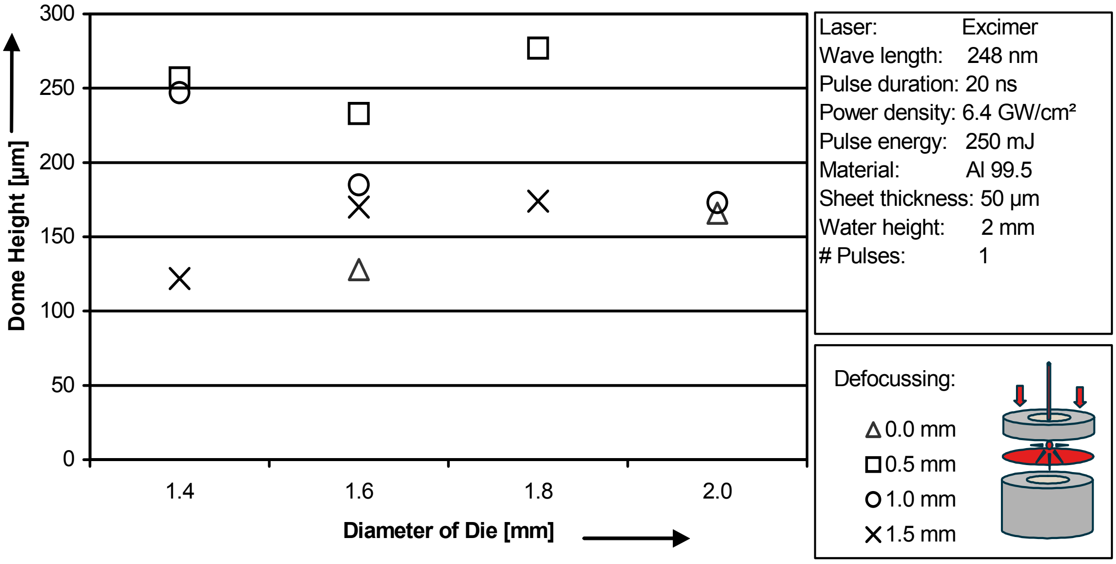
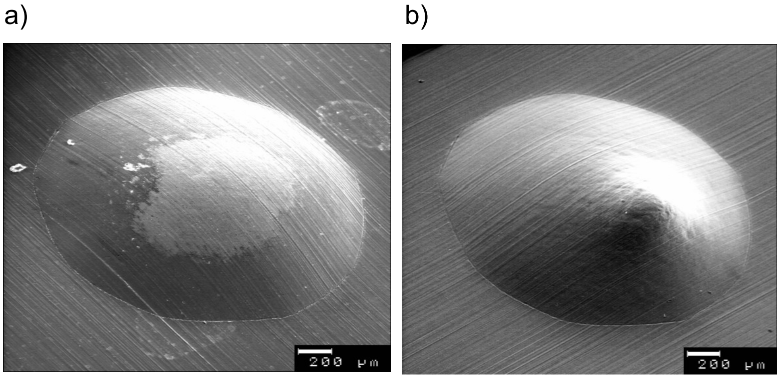


***Figure 6**: Dome height of laser stretch-formed parts depending on the defocussing (with use of a water film)*

3.2 Influence of the number of pulses

The use of one laser pulse for stretch-forming usually leads to a uniform dome shape of the part if a water film is used, see Figure 7a). All experiments where a second or more laser pulses were used lead to a second local forming, so that a peak in the dome can be seen, see Figure 7b). Eight pulses in this experiment lead to perforation of the sheet. The local forming in parts with more than one laser pulse could be explained by the fact that the surface of the parts is preliminary damaged at a local area through the first laser pulse. Ablation took place and the surface properties were changed at this point, resulting in a higher local absorptivity. The second laser pulse hence causes significantly higher ablation than the first laser pulse, so that the local thinning is much higher. The ignition of the plasma takes place after the thinning and then causes higher deformation at thinner points. The increased ablation might also be the reason for the non uniform forming of laser stretch-formed parts without a water film – as described in the previous chapter – since the water reduces ablation.


a) b)

Laser:	Excimer
Wave length:	248 nm
Pulse duration:	20 ns
Power density:	6.4 GW/cm²
Pulse energy:	250 mJ
Material:	Al 99.5
Sheet thickness:	50 µm
Water height:	2 mm
Diameter of die:	1.4 mm
Defocussing:	0.5 mm

Figure 7: *Shape of laser stretch-formed parts with a) one and b) two pulses*

3.3 Influence of the power density

The power density is proportional to the pulse energy and decisive for the forming result. The pulse energy of 250 mJ and thus the power density was reduced from 100% to 5% in the following experiments. It can be seen that the dome height tends to result in decrease with decreasing pulse energy. Unfortunately, the experiments show a certain scatter, since these are preliminary investigations. The forming still takes place at 5% of the power density, since 5% are three times the minimum power density for plasma ignition, see Figure 8. The decrease of the power density decreases the velocity of the shock wave, and thus the available forming energy.

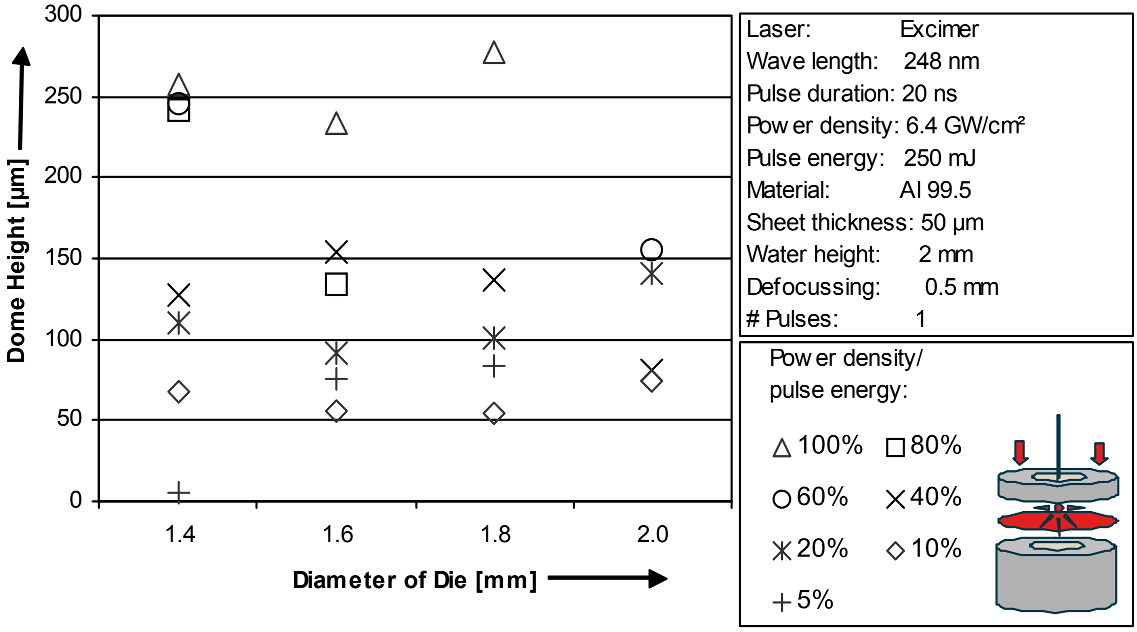


Figure 8: *Dome height of laser stretch-formed parts depending on the pulse energy*

3.4 Influence of the diameter of the die

An appropriate statement about the influence of the diameter of the die on the forming result for single test series cannot be made, since the number of experiments is too small. But a review of all experiments provides better statistical reliability. Figure 9 shows that the average dome height over all experiments, which resulted in a uniform dome shape, is almost the same for diameters of the die of 1.4, 1.6, 1.8 and 2.0 mm. The dome height can also be set in a relation to the diameter of the die, and the aspect ratio can be calculated. The aspect ratio is highest for parts with 1.4 mm in diameter and decreases with increasing diameter. This means that the highest forming degree could be reached with the smallest diameter of the die, which might be due to the fact that the shock wave is applied on a smaller surface, since the hole in the blank holder is smaller. Thus, more forming energy per area is available.

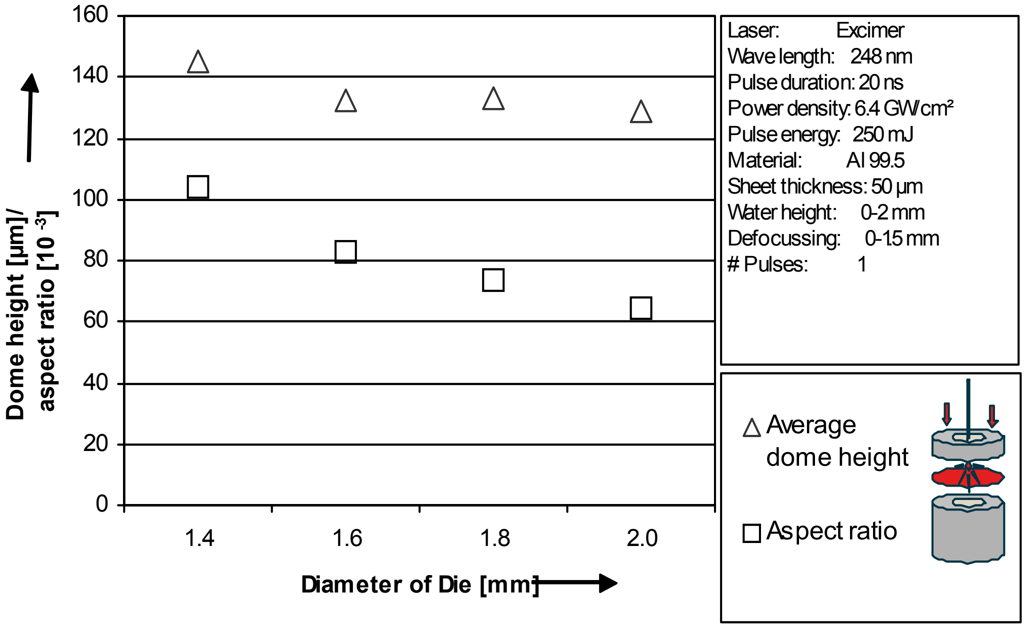


Figure 9: *Dome height of laser stretch-formed parts depending on the diameter of the die*

3.5 Influence of the material

In addition to the experiments with Al99.5 some experiments with stainless steel have been carried out. Figure 10 shows that the dome height of stretch-formed parts out of stainless steel remain under 25 µm, whereby parts out of Al99.5 reached a dome height of more than 250 µm. This is comprehensible, since the yield strength of the stainless steel is twice the yield strength of Al99.5, but the reduction of the sheet thickness of the stainless steel by 50% did not lead to better results. Another reason could be that the oxide film of the aluminium sheet allows a quicker ignition of the plasma and hence causes a more powerful shock wave.

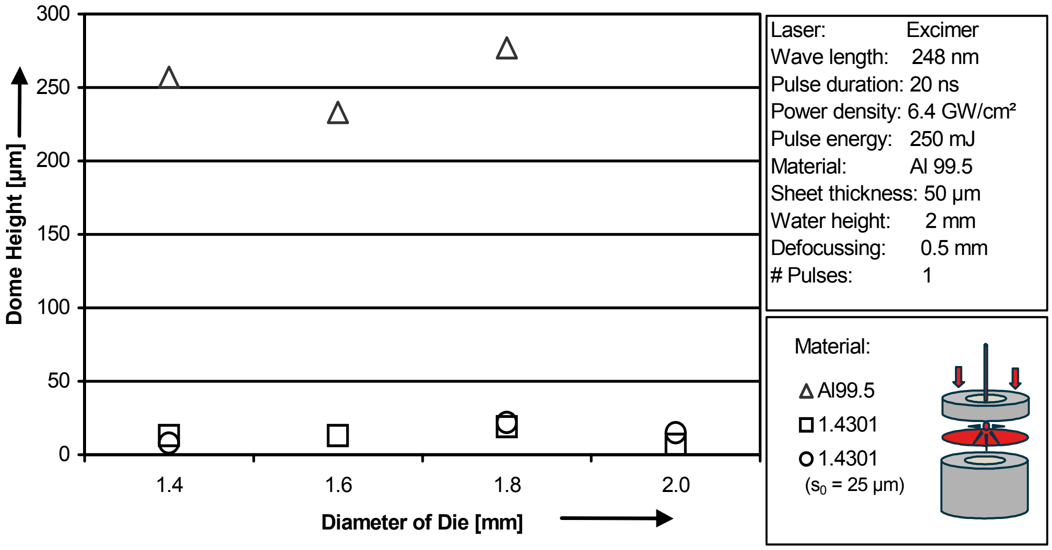


Figure 10: *Dome height of laser stretch-formed parts depending on the material*

4 Conclusions

1. Laser induced shock waves can be used for sheet metal forming as a high speed forming process in micro- and mesoscope.
2. Laser stretch-forming allows to form uniform shaped domes with heights over 250 µm and diameters of 1.4 mm of Al99.5 foils with 50 µm in thickness.
3. The use of a water film increases the forming degree, decreases the amount of ablation and therefore increases the quality of the formed shape.
4. The power density of laser radiation is directly related to the forming degree: A decrease in power density leads to a decrease in dome height in laser stretch-forming experiments.
5. The use of several laser pulses causes undefined, non-uniform shapes in laser stretch-forming, since the thinning through ablation is to high.

5 Outlook

The experiments show encouraging results, which can be used for further investigation in laser stretch forming. Influences like the inertia of the air in forming direction, geometry, and surface quality of the die as well as the reproducibility of the geometry of the work piece have to be investigated. Other sheet metal forming processes like bending and embossing provide a broad research field, and deep drawing with laser induced shock waves is imaginable. The processes have a high potential for bulk production, since today's excimer lasers have pulse frequencies up to 2 kHz. Lasers, which provide higher power densities, will probably allow even higher forming degrees than shown in this paper.

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