Forming Behaviour in Laser Shock Drawing*

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Abstract

Through the continuing trend of miniaturization new cost efficient and fast methods for processing small parts are required. In this paper a new non-mechanical process for the forming process of micro deep drawing is presented. This new deep drawing process utilizes a laser initiated plasma shock wave at the target, which forms the sheet. Several pulses can be applied at one point and therefore high forming degrees can be reached without increasing the energy density. In this paper the pressure of the shock wave is measured in order to enable optimizations of the process in future. Furthermore a distribution of the thickness over the deep drawn cups will be introduced. Finally laser deep drawing of samples made out of Al99.5, Cu and stainless steel sheet metal with thicknesses of 20 µm and 50 µm are shown.

Keywords

Micro forming, Laser forming, Deep drawing

1 Introduction

Within the ongoing demand of miniaturization of high precision components in electronics, precision mechanics, micromechanics and mechanical engineering the commercial relevance of the micro industry rises more and more. Read and write heads, inkjet printers, pressure sensors or micro fluidic chips are typical micro products in these industries. Within this increasing market the demand on productivity, efficiency, complexity and accuracy is growing. To this regard the well known advantages of high production rates, minimized material loss, excellent mechanical properties and close tolerances of the final product show the large potential of metal forming for micro parts [1]. Thus,

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investigations and improvements of conventional micro forming processes are needed, but also the invention of new processes is desirable. In this paper a new process of micro deep drawing by laser induced shock waves is introduced.

Laser shock treatment is already well known as a process for the modification of surfaces. Shot peening, i.e., got an increasing interest in the last years, since this technique can be used for the hardening of surface layer of components and especially for inducing residual compressive stresses. The modification of the material and its characteristics after laser shock treatment is already discussed in some basic works [2]. However, just some applications are known in the literature. This laser shock treatment was now extended to laser shock forming.

2 Principle of the Forming Method

Laser shock forming is a process, where the laser induced shock waves are used for a working step. While conventional laser forming is a process, where different thermal mechanisms cause bending of the sheet metal [3], laser shock forming takes place by a non-thermal mechanism. In this case the shock wave is used as a punch for the deep drawing process. At the laser shock forming the work piece is supplied with a laser pulse of high power density. The temporary pressure on the surface initiates an elasto-plastic shock wave onto the work piece and in consequence the shock wave pressure creates a forming of the work sheet. After the shock wave treatment no thermal effects on the surface of the sample can be detected [4]. This effect is taken beneficial for the laser shock forming.

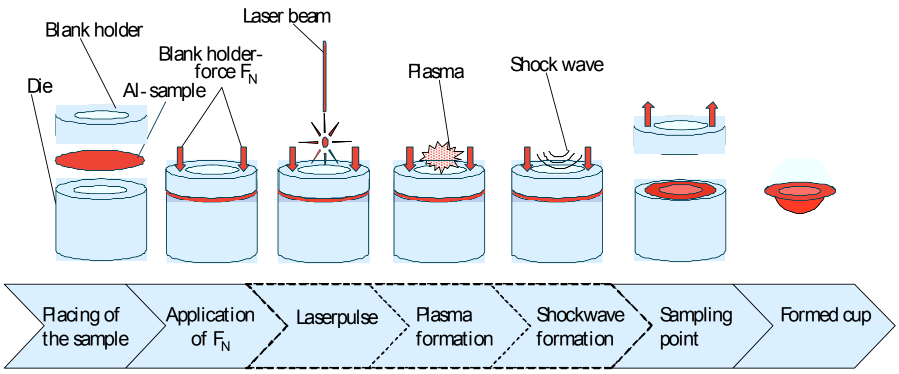


***Figure 1**: Principle of the laser deep drawing process*

The layout of the test blank for laser deep drawing is described by the following. A laser cut circular sheet metal is placed on a drawing die. The blank holder is placed onto the blank with a defined blank holder force below the clamping force. In a next step one or several short laser pulses of a TEA-CO_2-laser hit the specimen with the focus located at the blank surface. The high energy density of the laser radiation initiates ionization of the close-by atmosphere and thus plasma formation takes place. The propagation of the plasma causes a shock wave, if the energy density of the laser pulse exceeds a certain threshold. The principle of the laser shock forming can be seen in Figure 1.

3 The Shock Wave as a Tool

3.1 Pressure Measurement of the Shock Wave

The acting pressure of the plasma on the surface produces a shock wave at the solid body. The pressure caused by the laser introduced shock wave is the basic physical parameter for the plastic forming of the work piece. For the evaluation of the laser shock method the pressure is measured. The evaluation shown in this chapter can be used for future investigations to optimize the laser-caustic on the basis of the measured pressure. The pressure values can also be used for future simulations of the process or for an analytic model.

In order to detect the pressure under the surface of the target the following measuring method from Hintz [5] is used. For that a piezoelectric polyvinylidine fluoride (PVDF) sensor with an active area A of 1 mm², embedded in a PTFE foil, is bonded on the surface of a PMMA body, see Figure 2. The response rate is up to 10^{-9} Hz and therefore suitable for shock wave measurement. The 75 µm thick sensor film is located between the sample and a plexiglas body. For the calculation of the pressure the following term is used [5]:

$$p(t) = \int_0^t U(t')dt' \cdot \frac{1}{R} \cdot \frac{1}{C} \cdot \frac{1}{A} \tag{1}$$

A high resistance is applied to preserve the piezosensor:

- Resistance R = 1 MΩ

The following data of the piezosensor are used:

- Capacity C = 22.5 pC/N
- Active area A = 1 mm²
- Voltage signal U(t')dt' = [Vs]
- Pressure p(t) = [Pa]

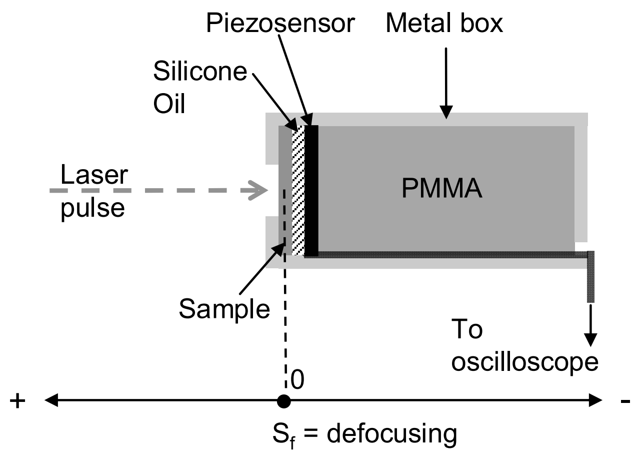


***Figure 2**: Schema of the pressure measuring with the piezosensor [5]*

Acoustic impedances are essential for the calculation of the absorbed intensity of the shock wave at the transition from one medium to another. The acoustic impedance of a material is determined by the density ρ of the material and the phase velocity c of a wave in this medium:

$$Z = \rho \cdot c \tag{2}$$

For a better coupling of the shock wave into the sensor, silicone oil is placed between sensor and sample. The PMMA body is hold in a metal box, which consists of a cylinder with a top to eliminate high frequency interferences, see Figure 2. The top is fixed by screws, which are tightened with defined 10 Ncm each. The PMMA body offers the development of the experiments without disadvantageous reflexions of the produced pressure wave. The laser beam is converged by a focused tilted mirror and the sensor signal is read by a digital storage oscilloscope.

At the two interfaces between sample, silicone oil and sensor reflexion losses of the shock wave occur. Hence, the pressure on the piezosensor is less than the pressure under the surface of the sample. A correction factor Z_U is calculated out of the acoustic impedances of aluminium Z_{Al}, of PMMA Z_{PMMA} and silicone oil Z_{Oil} to compensate these losses. For the ratio of the intensity of the pressure wave under the sample and after passing the sensor Z_U is [6]:

$$Z_U = \frac{(Z_{Al} + Z_{Oil})^2}{4Z_{Al}Z_{Oil}} \cdot \frac{(Z_{Oil} + Z_{PMMA})^2}{4Z_{Oil}Z_{PMMA}} = 4.55 \tag{3}$$

with Z_{Al} = 1.38 g/(cm²s)
Z_{PMMA} = 0.37 g/(cm²s)
Z_{Oil} = 0.121 g/(cm²s)

Hence, the corrected pressure p_r under the sample is:

$$p_r(t) = p(t) \cdot Z_U \tag{4}$$

The derivations of the formulas can be seen in [5]. With the stated values the pressure under the sample surface is therefore:

$$p_r(t) = 2.022 \cdot 10^{11} \frac{Pa}{Vs} \cdot \int_0^t U(t')dt' \tag{5}$$

For the calculation of the pressure under the surface of the sample the voltage signal is numerical integrated over the time and the pressure p determined by formula (5).

It becomes apparent that this measurement method is a complex measurement system, which obtains a comparable high statistical spread.

3.2 Results of the shock wave pressure measurement

In the following results out of the shock wave measurement are presented. The curves of pressure and the piezosensor signal shown in Figure 3 are generated by a shock wave. The shock wave was applied by a TEA-CO_2-laser pulse with a power density of 0.86 GW/cm² on an Al-sample with a thickness of 50 µm. The curves show the voltage and the pressure characteristics of the first shot on a sample. Over a period of fewer than 25 µs a pressure maximum of 2.5 MPa is achieved.

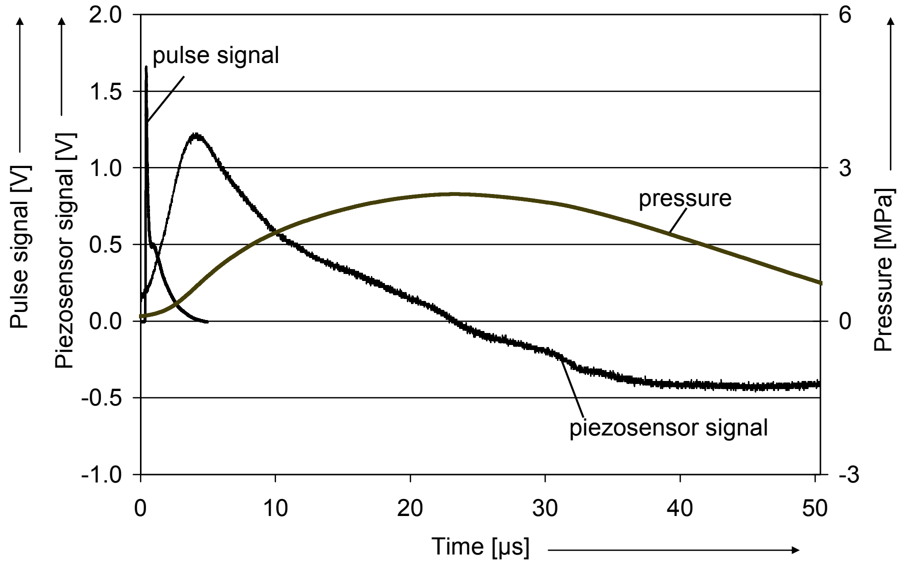


***Figure 3**: Typical signals of the pressure measurement; laser: TEA-CO_2; pulse energy: 3 J; spot size: 0.035 cm²*

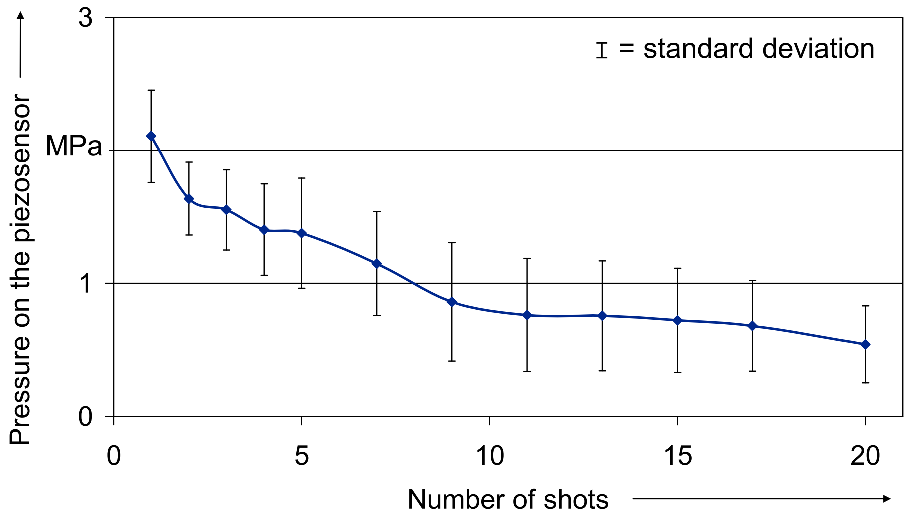


***Figure 4**: Influence of multiple exposure of one Al-sample on the measured pressure; laser: TEA-CO_2; pulse energy: 3 J; Al-Sample thickness: 50 µm; spot size: 0.035 cm²; number of experiments for each parameter: 5*

Furthermore, the influence of several pulses on an Al-sample on the pressure signal is investigated. Multiple exposures on Al-samples show that the first shot on a new sample achieves the highest maximum pressure value, whereas the measured pressure decreases for the following shots. This behavior is illustrated in Figure 4. The reason for this behavior is not found yet, but will be investigated in near future. In order to ensure consistent conditions for all measurements the target is renewed after the first shot in the following investigations.

Another potential influencing factor of the measurement process is the thickness of the used Al-sample, which is neglected in the correction factor in section 3.1. In order to investigate this influence on a potential difference between the real pressure values above the target and the measured values, experiments with different sample thicknesses were made. Figure 5 shows the measured maximum pressures under samples with thicknesses of 30, 50 and 100 µm. But a significant influence can not be identified. This might be caused by the comparable small sample thicknesses, which were used for laser shock forming: Within this sheet thickness range just a few grains are placed in the effective direction of the shock wave propagation. Therefore the sheet thickness in the investigated µm-area is not evaluated as a main influencing factor on the shock wave measurement.

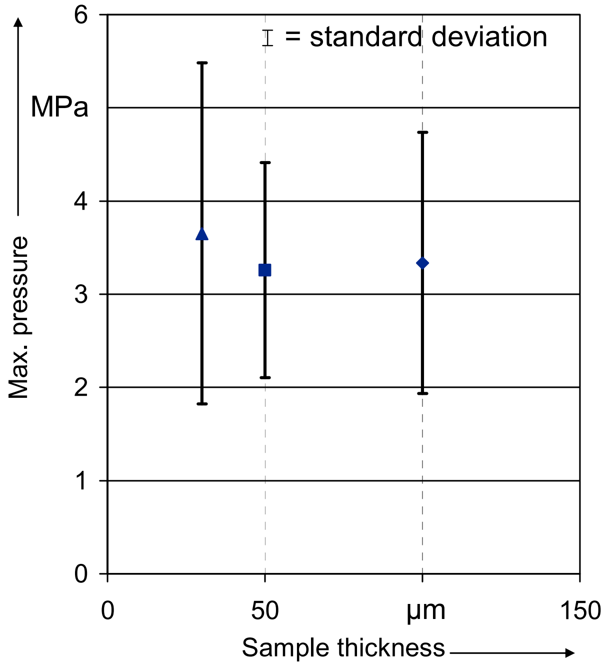


Figure 5*: Maximum pressure under Al-samples with different thicknesses; laser: TEA-CO_2; pulse energy: 3 J; spot size: 0.035 cm²; number of experiments for each parameter: 10*

The influence of the distance between sample and laser beam focus s_F (see Figure 2) is determined for a future optimization of the pressure impulse. Thus, the piezosensor is positioned between 3 mm under (focal position s_f < 0 mm) and 60 mm above the focus in different steps.

Figure 6 shows the spot size for different focal positions and the corresponding measured maximum pressures. All pressures of the shock wave initiated 3 mm under to 7 mm over the focus position are at the level of 3.5 MPa. At a defocusing of 8 mm above the target, the measured pressure decreases, it stays above 2.5 MPa, even at a focus to target distance of 40 mm. It becomes apparent that the process itself is stable: The shock waves initiated above the focus show constantly values of 2.5 and 3.5 MPa up to 40 mm defocusing. Even when the spot size increases the pressures are at a high level. Due to the constant pressure for a defocusing above s_F = 0 mm a correction of the focal position during deep drawing with multiple pulses is not necessary. Also the adjustment of the focal position does not play an essential part.

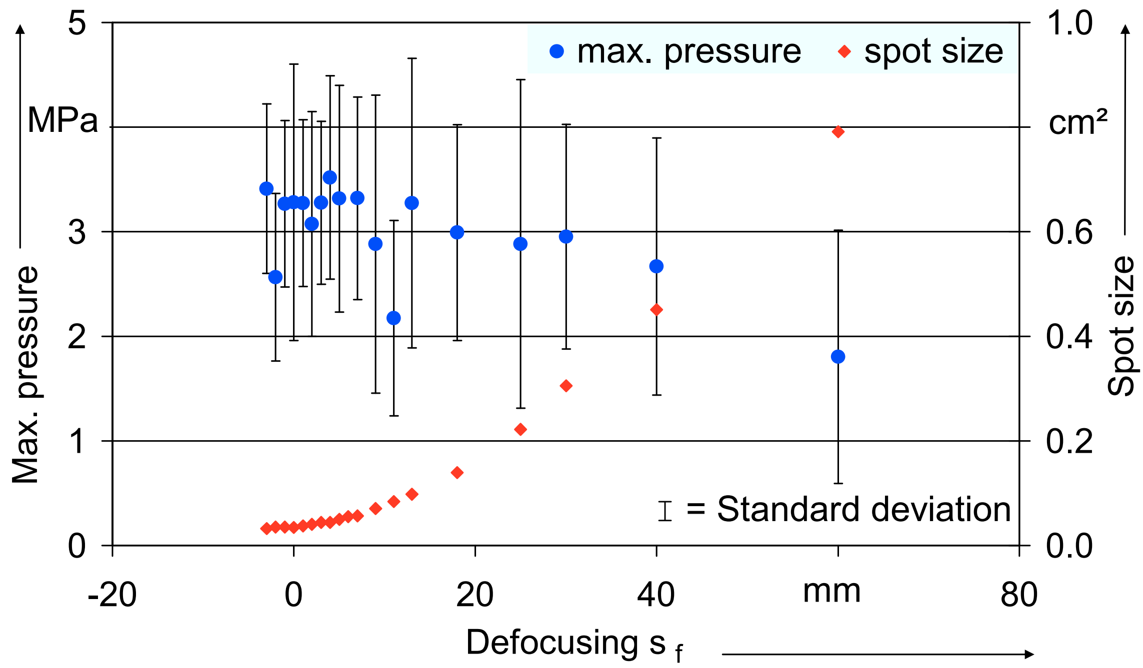


Figure 6*: Pressure depending on defocusing; laser: TEA-CO_2; pulse energy: 3 J; Al-Sample thickness: 50 µm; number of experiments for each parameter: 10*

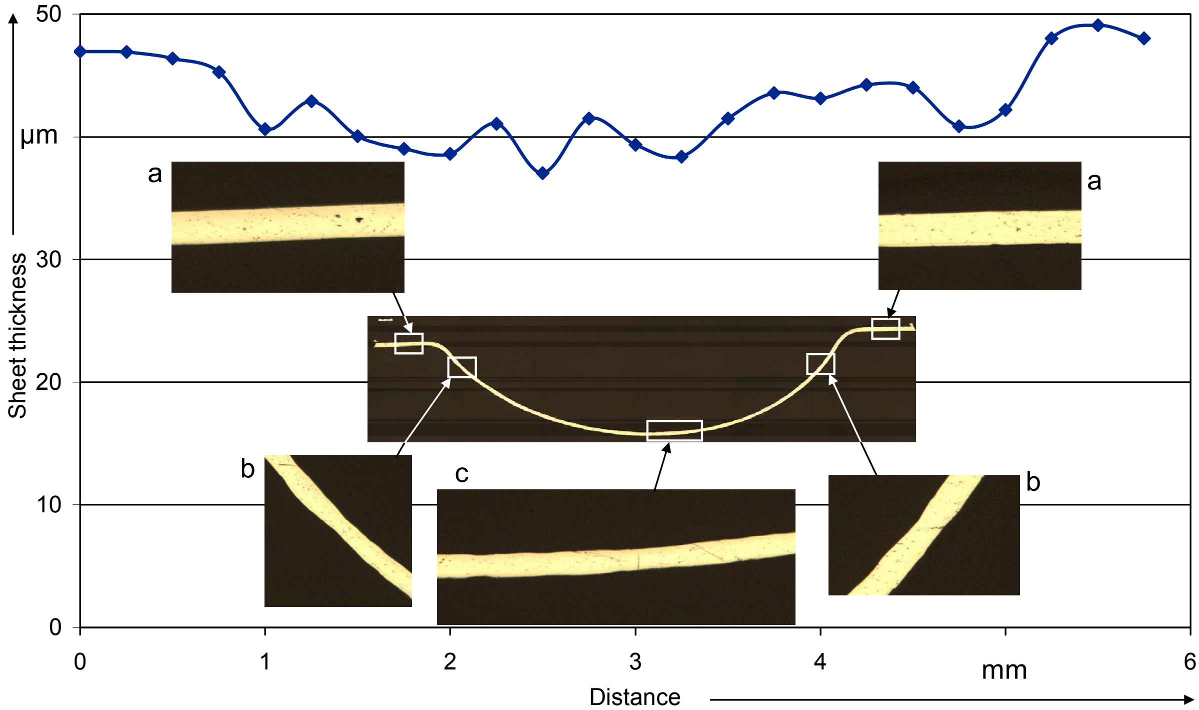
For a classification of the achieved pressures in the literature, the presented results are compared to results from Hintz [5] and a calculation of Hein [7, 8]. Hintz used the same pressure measurement system, but under different conditions. Hintz achieved pressures of 70 MPa at a pressure measurement of the shock wave initiated at free ablation. In comparison to the presented pressure values of 3.5 MPa a factor of 20 can be discovered by the same spot diameter. Hintz used an Excimer-laser (wave length 308 nm) with a laser beam energy of 2 J with a pulse duration of 45 ns and a pulse rising time of 1-3 ns. In contrast to that, the pulse duration of the TEA-CO_2-laser (wave length 10600 nm) is 100 ns and the pulse rising time is 35 ns. With the longer pulse duration and the longer rising time, the TEA-CO_2-laser the energy part, which is coupled into the plasma is less and thus the pressure of the shock wave is less. Hence, the measurement values are realistic.

A further classification can be made by the formula of Hein [7, 8] for the bursting pressure of a spherical cap in the hydroforming. The comparison makes sense, since the hydroforming process of forming spherical cups is the same like in the shock forming process. The calculated maximum pressure for a spherical cap in the presented case is 1.4 MPa. Thus, the measured pressures are located at a reasonable level.

4 Forming behaviour

4.1 Analyse of forming behaviour of deep drawn cups

In comparison to the presented method the deformations in the mechanical deep drawing process are affected by the die. The result is a distinctive deformation gradient at local positions, which implicates a smaller sheet thickness. For a further development of the laser shock forming it is significant to see how the initiated forming is located in the laser shock formed sheets.



Laser:	TEA-CO_2	Initial thickness:	47 µm	Change in diameter:	1.7 %
Wavelength:	10600 nm	Initial diameter:	6 mm	Blank holder force:	10.2 N
Pulse energy:	600 mJ	Drawing ratio:	1.5	Number of shots:	120
Material:	Al99.5	Drawing radius:	0.25 mm	Uncertainty of measurement:	2 µm

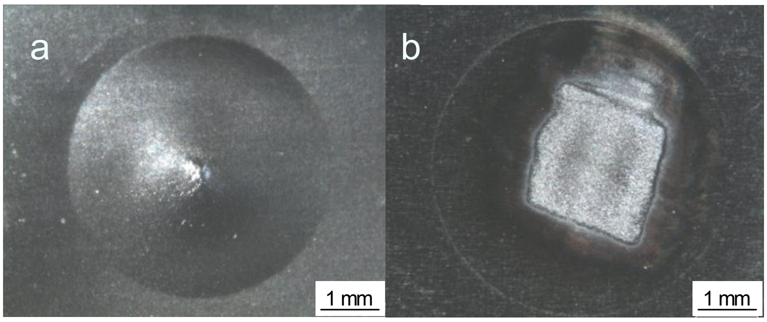
***Figure 7**: Distribution of the thickness of a characteristic laser deep drawn cup*

Therefore the sheet thickness is plotted over the length of a characteristic deep drawn cup (Figure 7). The flange area (a) shows a uniform behaviour, while the escape of the drawing radius (b) on the left and the right side shows a necking of the sheet. In the bottom area (c) the sheet thickness varies in a wave form. This wave formed bottom is due to the orange peel that can be detached at the surfaces of the samples (i.e. Figure 9 b). Furthermore the comparably small change in the sample diameter after the forming process of 1.7 % shows that the process has a higher stretch-forming component than a deep drawing one. The global decrease of the thickness shows that within the forming process the yield stress is achieved over the whole length of the cup. The material for the forming is taken from the entire width of the sample.

4.2 Forming behaviour of different materials

In order to investigate the applicability of the laser shock forming beyond Al 99.5, first results of processing stainless steel (1.4301) and copper were shown in this chapter.

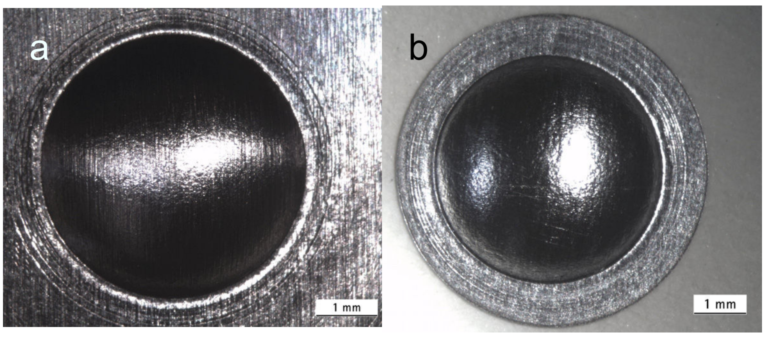
In Figure 8 images of samples out of stainless steel with a thickness of 20 µm and 50 µm and in Figure 9 images of samples out of copper and aluminium with a thickness of 50 µm are shown. The samples are treated with similar parameters, whereas the stainless steel and copper samples are stretch formed and the aluminium is deep drawn.



Laser:	TEA-CO2
Wavelength:	10600 nm
Pulse energy:	3 J
Material:	1.4301
Blank holder force:	4 N
a) Thickness:	20 µm
# pulses:	25
b) Thickness:	50 µm
# pulses:	700

***Figure 8**: Stainless steel samples out of with different number of pulses*

The sample out of stainless steel with 20 µm thickness (Figure 8a) shows a minimal deformation of 100 µm in cup height. The sample with 50 µm thickness (Figure 8b) shows no visible deformation after it was subjected to a 700 pulses. After 700 pulses a high damage of the material is noticeable, but still no deformation occurs. In contradiction to that the 50 µm copper sheet can be formed as well as aluminium (Figure 9a). With the same parameters copper shows a 1.5 times smaller cup high than the aluminium (Figure 9b), which is due to the higher yield strength of the material. However, high forming degrees up to the forming limit can also be reached with copper by the use of more pulses.



Laser:	TEA-CO2
Wavelength:	10600 nm
Pulse energy:	3 J
Thickness:	50 µm
a) Material:	SE-Cu
Blank holder force:	4.56 N
# pulses:	9
Cup height:	0.66 mm
b) Material:	Al99.5
Blank holder force:	4.1 N
# pulses:	9
Cup height:	1 mm

***Figure 9**: Copper (a) and aluminium (b) samples with the same parameter*

In contradiction to that, the yield strength of the used stainless steel was obviously too high. The calculated pressure after Hein [7, 8] for bursting is here 240 MPa (for s_0= 20 µm, cup height 100 µm). Therefore the reached forming pressures of laser shock waves of about 3.5 MPa (chapter 3) are not sufficient. An increase of the forming pressure will probably not bring better results, since the surface of the stainless steel is already damaged by the used shock wave pressure. Thus, further investigations with steel are not effective with the present setup.

Since the yield stress of copper is comparably low, the forming of copper is much easier to achieve. The higher ductility of copper in comparison to aluminium results in a smaller elongation ratio, but later crack formation than aluminium. This shows a further potential for copper in the laser shock forming. Thus, the application of laser shock forming with copper makes the process especially interesting for the electronic industries.

5 Conclusions

- Pressure measurement of the created shock wave was introduced, showing that pressures at the level of 3.5 MPa can be created with TEA-CO_2-lasers.
- An influence of the thickness of the Al-samples in the measurement process of the pressures is not detectable.
- An increasing number of exposures of one sample decrease the measured pressures.
- The pressure of the laser induced shock wave is not sensitive to defocusing during the deep drawing process in arrange of -3 mm to 7 mm.
- The distribution of the thickness of a characteristic laser deep drawn cup shows necking at the left and right side of the cup and a non-uniform behaviour at the bottom.
- The investigation of the applicability of the laser shock forming shows a good suitability not only for aluminium, but also for copper.

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