Determination of Forming Speed at a Laser Shock Stretch Drawing Process

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Abstract

Laser shock forming is a new high speed forming process based on TEA-CO2-laser induced shock waves. In former publications laser shock forming was already presented as a process which can be used for deep drawing, stretch drawing and cutting of thin copper and aluminum sheets. The process utilizes an initiated plasma shock wave on the target surface, which leads to the sheets forming. Several pulses can be applied at one point in order to achieve a high forming degree without increasing the energy density beyond the ablation limit. During the process, pressure peaks in the range of some MPa can be achieved. In order to classify the process in the framework of high speed forming processes, the temporal varying deformation velocity due to different materials have been identified based on a stretch drawing process by using different pulse energies. Therefore a new high speed measurement system based on the shadowing effects is designed and its suitability is shown. The determined strain rate of 520 s-1 meets one of the criteria for the classification of laser shock stretch drawing as a high-speed forming process.

Keywords

Forming speed, Strain rate, Laser shock forming

1 Introduction

The trend towards miniaturization, especially in the electronics industry and medical technology, continues. Geiger et al. (2011) recognized that innovative ideas and new developments in this field have great potential to intensify this trend. Thus, for example in each generation of smart phones more functions are integrated with nearly unchanged dimensions of the device itself. Hoffmann (2006) stated that the trend of miniaturization includes the necessity to produce small high quality components in fast and reliable manufacturing processes. Krause (1995) demonstrated that forming processes are particularly suitable for mass production of micro metal parts, due to the short production times, possibility of automation and the improvement of the material properties e.g. by work hardening.

The potential to realize short process times is also provided by high-speed forming. First applications were already made in the 19th century. Munroe (1888) for example described how the detonation of explosive material over a stamping die can be used for engraving processes. Due to the required safety measures and the long setup times, the use of explosive materials is not suitable for mass production. One possible alternative is laser shock forming. There are different possibilities for laser shock processes. Laser shock forming using a TEA-CO_2-laser is a well-known process, such as the works of Schulze Niehoff et al. (2005). Due to thermo- and field emission electrons are irradiating out of the surface. Collision processes between these highly energetic electrons and atmosphere molecules are producing ions, which are absorbing the ongoing laser radiation. Miziolek et al. (2006) described that these free ions and electrons absorb energy by inverse bremsstrahlung absorption and can produce further ions and electrons by impact processes until an optical breakdown and thus a plasma formation is achieved. The inverse bremsstrahlung increases with the square of the wavelength accomplishing a nearly complete absorption of the longer wavelength of CO_2-laser light by the plasma. This process offers the possibility of high speed mass production of micro parts. Wielage (2011) characterized the process and identified the fundamentals of the process design for the manufacturing of small metal parts. Vollertsen et al. (2009) demonstrated, that the production of micro components result in so-called size effects, which are leading to difficulties in scaling down the forming processes to the micro range. To use laser shock forming for industrial processes, an accurate understanding of the process is necessary for using it effectively and economically.

An important process parameter is the strain rate of the forming process. For the measurement of the strain rate, the deformation velocity has to be determined. Wielage determined also the strain rate for a laser shock bending process for different pulse energies using a high speed camera. The determined strain rates are in the range from $1 \cdot 10^3 \cdot s^{-1}$ to $2 \cdot 10^3 \cdot s^{-1}$. Due to the size of the high speed camera, the accessibility to the process is not given. Numerous studies show, that different high speed measuring systems are known which have extremely high operational costs, such as the works of Fenton et al. (1998) and Bessonov et al. (2004). Beerwald (2005) described a modified system for high speed measurement of strain rates in the electromagnetic forming, based on the measurement setup of Finkenstein et al. (1967). This is an optical measurement principle which is based on the shadowing effect, wherein a line laser is used as a light source. In this work, a measurement method for the determination of the deformation velocity in a laser stretch drawing process is designed, implemented and validated. Actual systems are restricted to the measurement direction and the accessibility to the process. Therefore in this investigation the measurement principle based on the shadowing effect will be used and the feasibility of this method for the micro range will be investigated.

2 Method

2.1 Measurement Principle

A schematic representation of the technique, which is used in this study, is shown in Figure 1. The Setup consist of three major parts: the measurement laser, the specimen which will be deformed and the sensor. The measurement laser, which is a diode laser with a wavelength of 650 nm and an average output power of 10 mW, is irradiating directly onto the sensor surface. The sensor, a position sensitive device (PSD-sensor) from First-Sensor, is providing an analogue voltage value proportional to the amount of laser light irradiating onto it. The measurement frequency of the PSD-sensor is 250 kHz. The specimen is placed between the measurement laser and the PSD-senor. When the specimen is deformed the amount of laser light irradiating on the PSD-sensor is reduced, thus decreasing the analogue signal in the same manner.

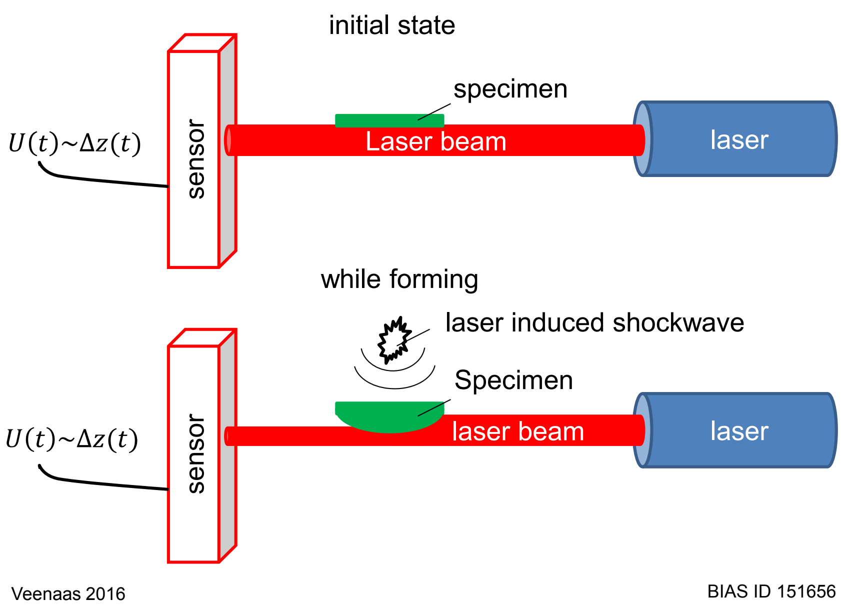

***Figure 1**: Schematic representation of the measurement principle*

2.2 Measurement Setup

The experimental setup is shown in **Figure 2**. The used laser is a TEA-CO_2 Laser (TEA = Transverse Excitation at Atmospheric Pressure) with a wavelength of 10.6 µm, a maximum pulse energy of 6 J and a pulse duration of 100 ns. The laser is irradiating onto the surface of the specimen.

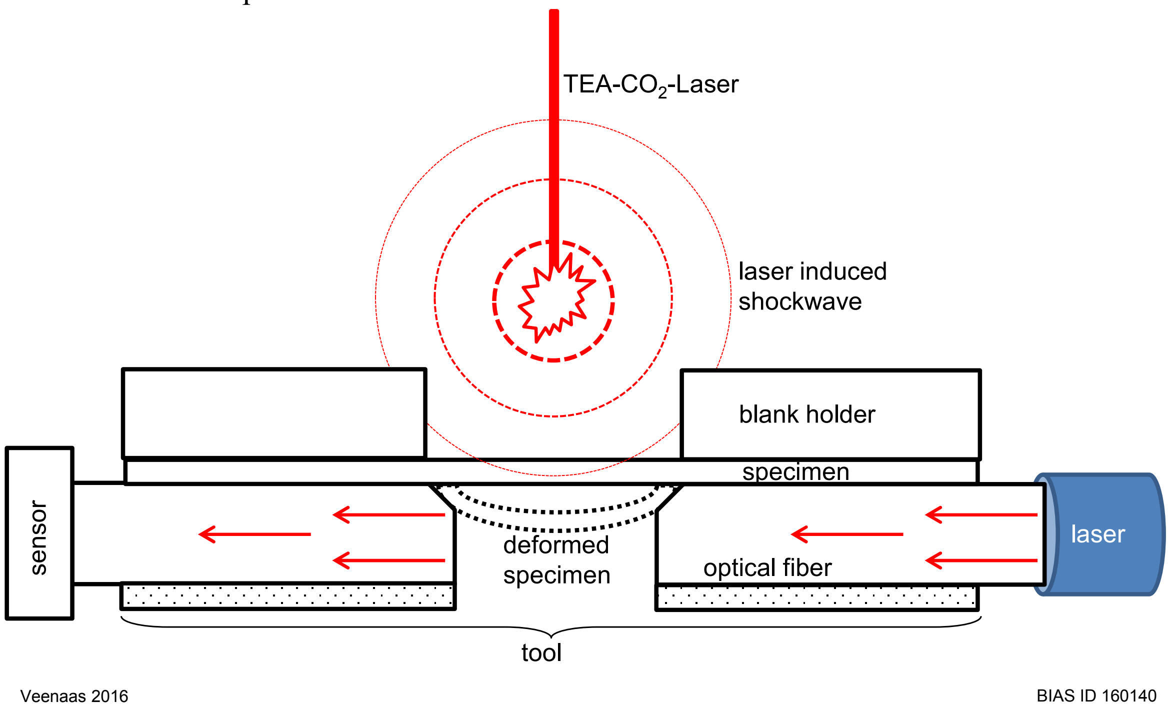

***Figure 2**: Experimental setup*

As shown in **Figure 2**, the measurement system is integrated into the forming tool. The laser is guided through an optical fibre. This optical fibre ensures the correct alignment of sensor and laser, which makes the measurement system more stable against disturbances. The chamfer at the optical fiber is needed for the forming process. Due to this chamfer the measurement range of the sensor is reduced, because of a different refraction behaviour of the laser light. The calibration of measurement system is done with a micro forming machine by using a punch with a round geometry for the shadowing. The travel speed of the punch is 1 m/s. The standard deviation of the measurement system is 2 %.

The height of the formed cups is measured with a contact free optical 3D laser scanning microscope (Keyence VK-X210).

2.3 Determination of Strain Rate

To determine the strain rate it is necessary to measure the strain itself. As shown in **Figure 3** from a cross section the deformation area D is measured which is the diameter of the dome. This value is taken as a reference for the determination of the average strain. Beginning at the edge of the dome the length of the center layer L is measured, using Olympus Image

Analysis Software Stream Enterprise. The center layer L is compared to the deformation area D for the calculation of the average strain. In this case an ideal stretch drawing process is assumed.

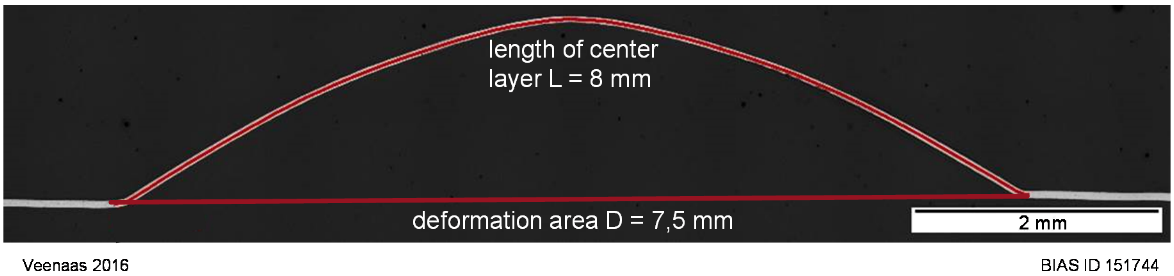

Figure 3*: Cross section of a formed dome and strain determination method*

Using this average strain the strain rate is calculated by:

$$\varepsilon = \frac{(l_1 - l_0)}{l_0} \tag{1}$$

$$\dot{\varepsilon}(t) = \frac{\mathrm{d}\varepsilon}{\mathrm{dt}} = \frac{d}{dt}\left(\frac{l(t) - l_0}{l_0}\right) \tag{2}$$

3 Results

In **Figure 4** the parts produced by laser shock stretch drawing are shown. Only the aluminum sheets with a thickness of 50 µm and the copper sheets with a thickness of 20 µm are leading to evaluable results. For aluminium sheets with a thickness of 20 µm the used laser pulse energy is too high, thus the material is breaking. For the copper sheets with a thickness of 50 µm the height of the formed cup was too low, thus the shadowing of the sensor was not evaluable.

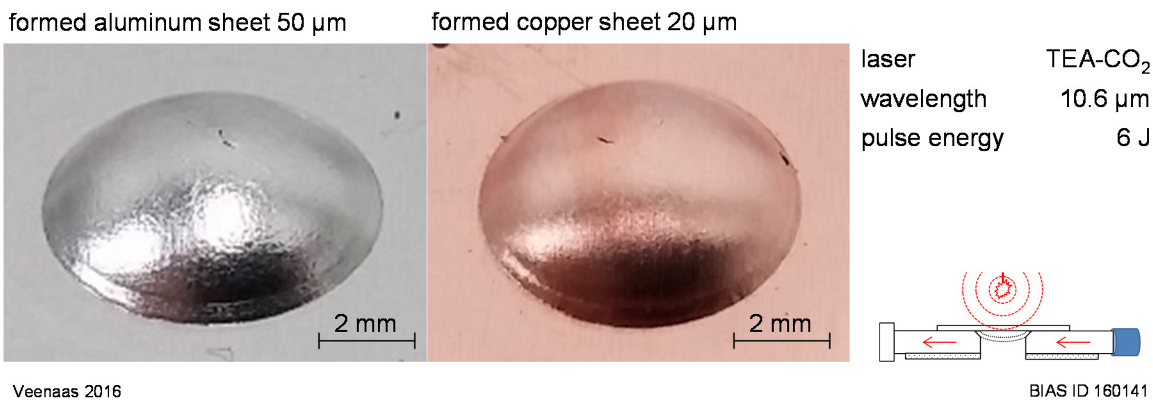

Figure 4*: Laser shock stretch drawn cup out of Al99.5 (left) and E-Cu 58 (right)*

A representable voltage over time signal recorded by the PSD-sensor during the laser induced forming process is shown in **Figure 5**. It can be seen that the signal is decreasing exponentially over time. The value drops from 1.14 V to 0.97 V in a time period of 128 ms.

The height of the formed cup, measuring 1.29 mm, was determined using a 3D laser scanning microscope. Using the measured height h_{cup} and the time for the forming process t_{form} the deformation velocity v_{form} can be calculated by:

$$v_{form} = \frac{h_{cup}}{t_{form}} \tag{3}$$

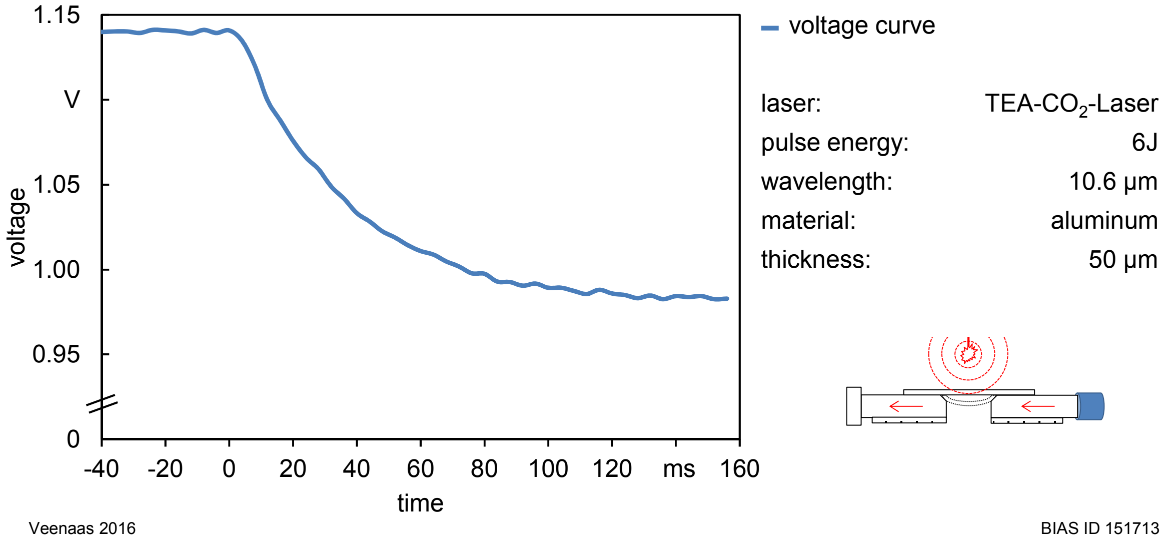

***Figure 5**: Voltage over time signal for Al99.5 with a thickness of 50 µm*

As described in section 2.2 the chamfer in the forming tool, the measured decrease of the signal does not represent the correct forming value. For the determination of the correct forming value the reduced signal due to the chamfer has to be compensated. Therefore an exponential function is used to determine the absolute value for the time period of forming, this is shown in **Figure 6**. Due to this exponential fit, the forming behaviour can be observed and an estimation of the total forming time t_{form} and height can be made.

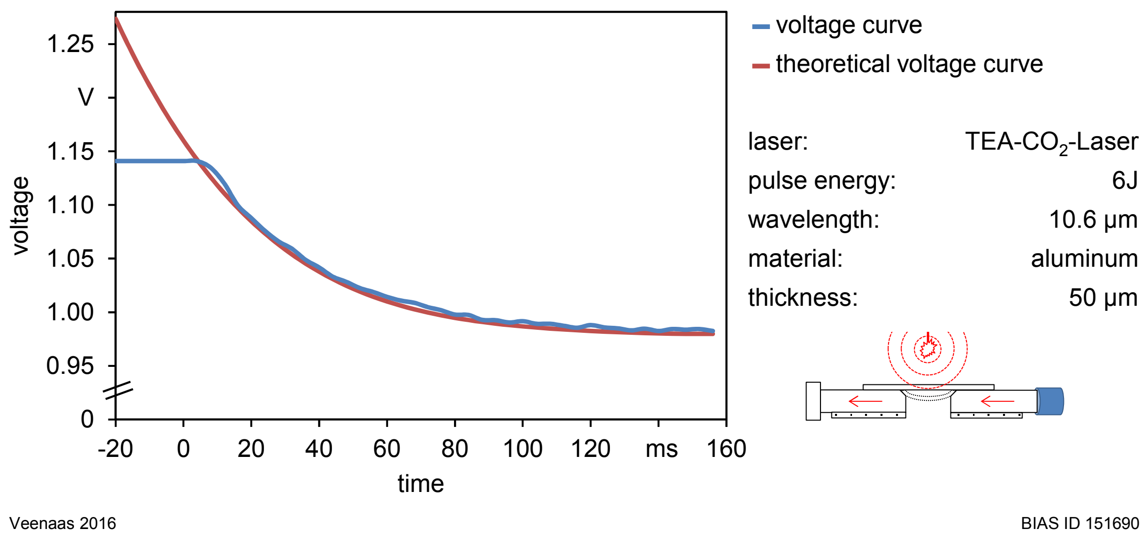

***Figure 6**: Exponential fit of the signal*

By using this procedure the time period of forming is increased to 148 ms, which is reducing the average deformation velocity of the forming process. Using equation 3, the corrected forming velocity of an Al99.5 sheet with a thickness of 50 µm and a copper sheet with a thickness of 20 µm can be seen in **Figure 7**. In this figure different pulse energies were used. Based on this data it can be seen, that the average deformation velocity is increasing with increasing pulse energies. For calculating the deformation velocity a uniform movement of the material is assumed. Therefore the determined deformation velocities are average deformation velocities of this process.

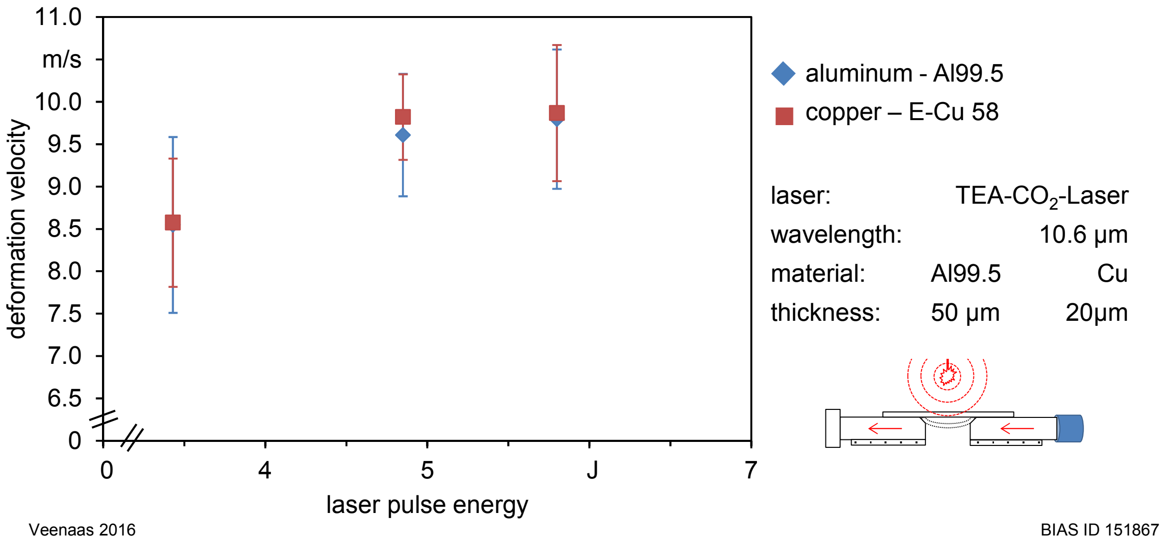

***Figure** 7: Deformation velocity and dome height of Al99.5 with a thickness of 50 µm*

For an Al99.5 sheet with a thickness of 50 µm and for the E-Cu 58 sheet with a thickness of 20 µm the strain rate is in the same range and could be determined as $\dot{\varepsilon} \approx 520\ s^{-1}$.

4 Discussion

Wielage stated that for the definition of a high speed forming process, in addition to the workpiece speed and the pressure rise time, the strain rate can be used. To be classified as high-speed forming the strain rate has to be inside the range of $10^2\ s^{-1}$ to $10^7\ s^{-1}$. The determined strain rate of 520 s^{-1} meets this criteria for classification of laser shock stretch drawing as a high-speed forming process. This value is a function of the measured deformation and the resulting strain on one hand, as well as the measured forming time on the other. The determined strain rate compared to the strain rate which Wielage determined for a laser shock bending process is lower. This can be explained by the different forming conditions, during the process. For a bending process, the deformation energy is lower than the deformation energy in an axially symmetric stretch drawing process. Thus more energy is left for the deformation of the bending part, which leads to a higher deformation velocity. On the other hand, for the stretch drawing process more deformation energy is needed for the forming process, which leads to a lower deformation velocity and hence to lower strain rates.

Figure 7 shows the average deformation velocity as a function of the pulse energy. It is shown, that the average deformation velocity is increasing with increasing pulse energies. However, this behaviour is not linear. With an increase from 5 J to 6 J the average deformation velocity is nearly the same. The average deformation velocity is calculated by the dome height and the time for the forming process. Due to work hardening, the increase of dome height using pulse energies from 5 J to 6 J is also smaller, which is also influencing the average deformation velocity.

Figure 5 shows the Voltage over time signal of the measurement sensor. Based on the exponential decrease of the signal, it can be seen, that the forming of the sheet does show the same behaviour. Due to the laser induced shock wave the deformation velocity of the material reaches the highest value at the beginning of the forming process. The signal of the sensor is based on the area of shadowing, which is a result of the forming of the cup. The form of the cup is cone-shaped, thus the area which is shadowed should be increasing with increasing deformation of the cup. This behaviour cannot be observed in the signal sequence. Because of the optical fibre, the measurement width is 3 mm which is reducing the described effect. Also the deformation velocity during the process is more significant than the effect of shadowing, thus the signal is showing an exponential decrease. Therefore the deformation at the beginning does have the highest value, which is than exponentially decreasing.

Due to the chamfer at the forming tool, the beginning of the forming process cannot be observed. By using an exponential fit this behaviour can be extrapolated. This procedure enables the determination of the beginning and the end of the forming process. Thus the average strain rate and deformation velocity can be calculated using this information. Due to the exponential behaviour of the deformation velocity, the maximum strain rate cannot be calculated. Therefore the strain and forming behaviour during the process must be known, which is not investigated yet. For this reason only an average value for the strain rate is determined.

Measurement systems for high-speed measurements are widely used in the industry and serve different applications. The achieved temporal resolution and the accuracy of these systems are suited for high speed forming processes. However, a necessary condition is the accessibility of the measurement system on the axis which will be measured. For example a laser triangulation must be installed under the forming tool to measure the sample from below. In addition, it would be necessary to decouple the system from the workbench to avoid vibrations and shock waves on the position-sensitive triangulation. This problem does not occur when using the present measurement system based on the shadowing effect. The integration of this sensor into the tool is leading to stable measurement conditions, which are not affected by vibrations. Also the accessibility for different measurement systems is give, thus this system can be used in combination with e.g. optical strain measurement systems.

Due to the calibration with a micro forming machine the uncertainty of measurement is below 2.5 % for deformation velocities of 1 m/s. The uncertainty of measurement for higher deformation velocities is in the same range, due to the qualitative progress of the voltage curve for different velocities.

5 Conclusion

- The measurement system, based on the shadowing effect, is well suited for the determination of the deformation velocity during a laser shock stretch drawing process.
- The uncertainty of the measurement is below 2.5 % for absolute average deformation velocities of 1 m/s.
- The strain rate of 520 s^{-1} classifies laser shock stretch drawing as a high-speed forming process.

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