Electrohydraulic extrusion of spherical bronze (CuSn6) micro samples

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Abstract

Conventional material testing strategies are time and cost intensive. In this paper, a new method for contactless high-speed testing of spherical micro samples by an electrohydraulic punch is introduced. The punch transfers the punching force incrementally to extrude the samples stepwise in dies with high aspect ratios. The sample's material behavior is characterized by analyzing the deformation behavior between the extrusion steps and at different forming stages.

Keywords

high-throughput material testing, bulk forming, micro parts.

1 Introduction

The development of new materials is a time and cost intensive iterative procedure. Hence, high-throughput technologies, as already known from chemistry or medicine research, are claimed (Mädler, 2014). Novel processes like single droplet solidification (Ellendt, 2016), laser supported additive manufacturing (Vetter, 2017) and rapid alloy prototyping (Springer, 2012) enable a fast generation and modification of small material samples. However, the characterization of these new materials is a crucial issue for the diverse material properties to be tested (Beinhauer, 2017). Not only the materials testing should be accelerated, but also the amount of material that is destroyed like in conventional testing processes e.g. tensile tests, should be reduced. A promising solution is found using the incremental electrohydraulic extrusion. This new process enables the characterization of micro samples by incremental forming into deep dies with different forming stages that represent defined stress and strain loads. The comparison of the occurring deformations with simulation results enables the determination of characteristic values that describe the material behavior.

Conventional extrusion of micro samples is restricted by the force transmission from the punch to the micro sample. Due to a high aspect ratio between channel diameter and length, the mechanical punch must also provide this high aspect ratio and tends to brake when the dimensions of the probe are downsized to submillimeter dimension. In addition, as the micro samples are spherical due to the high-through-put samples production, a proper force transmission between punch and sample without damaging the sample becomes difficult. Consequently, a new testing procedure has to be investigated. Shock waves are an alternative approach rendering the set-up more flexible to different die and sample geometry. They also eliminate the fracture problem of high-aspect ratio punches, Fig. 1. Two reasons demand incremental forming with consecutive steps. Firstly, the energy cannot be transferred within one single step while forming into dies with high aspect ratio and multiple forming stages. Secondly, the geometry of the samples has to be measured between each forming step in order to determine the characteristic values of the material.

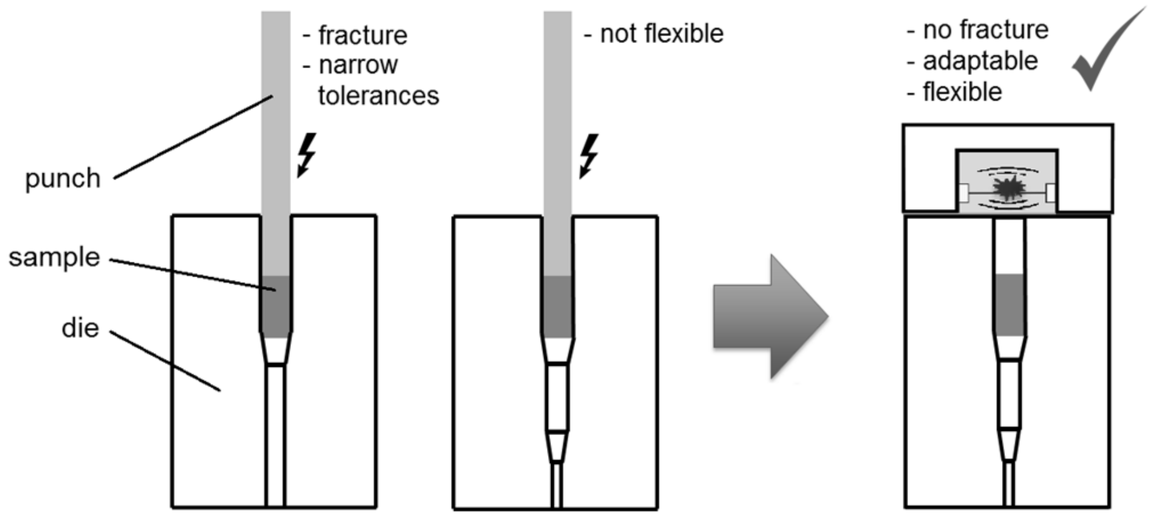

Figure 1: *The motivation for electrohydraulic bulk forming*

Forming operations with shock waves are well investigated for tube and sheet metal forming in macro dimensions (Wilson, 1964). These processes are conventionally used to deform huge parts for example from the automotive industry. One approach to provide a shock wave is to explode a wire in a water filled pressure chamber. A minimum energy E_V to vaporize the wire is required for electrohydraulic forming. In common applications an electrohydraulic shock wave is usually aimed to be as high as possible which is reached by increasing the loading energy E_C above the vaporization energy ($E_C >> E_V$). The resultant shock wave acts as a flexible hydraulic punch and can also be used for bulk forming in micro dimensions. Requirements for conventional micro bulk forming like narrow tolerances between punch and die, a precise guiding as well as the requirement of a high stiffness of the mechanical punch become obsolete. In the process, the electrohydraulic punch provides high pressures up to several GPa (Golovashchenko, 2013) and transmits the punching force contactless in the period of a few microseconds. This force accelerates the sample towards the extrusion die. By the impact of the sample on the die, the material is decelerated and the kinetic energy is transformed into deformation energy. Generally, the required energy for deformation is provided completely by the initial electrical discharge and the resulting reactions in the arising plasma.

In order to measure the deformations of the sample, a suitable measurement approach is required. The measurement should be able to deliver areal information about the material deformation from the surface of the sample inside the forming die. Only optical systems are appropriate for such measurements, but they require an optical access to the sample surface. This can be achieved by replacing parts of the forming die with transparent materials such as sapphire glass, which are able to withstand the shock waves and the friction loads by the material flow. With such an optical preparation of the forming die, speckle photography represents a suitable measuring method for the expected surface deformations. The speckle photography method is based on the interference of coherent light rays in the image plane of a camera system, resulting in a granular intensity distribution (speckle image) (Ennos, 1984). The light rays originate from a laser beam, which is directed on and reflected by the rough sample surface. Each of the resulting speckles can be regarded as a surface marker, since it moves with the surface as long as only small deformations and shifts occur. Therefore, an evaluation of the speckle movements resulting from the forming step delivers the areal deformation distribution of the surface (Peters, 1982; Kammers, 2013; Tausendfreund, 2015). As the correlation between the movements of the surface and the speckles is only valid for small movements, the extrusion step sizes should be limited to max. 100 µm. This technology can be implemented as an in-situ measurement system in order to achieve a high testing throughput.

Due to the aim of extrusion in small steps into deep dies with multiple stages, the shock wave energy needs to be controllable in a wide range even down to very small values with $E_C < E_V$ without changing e.g. the exploding wire diameter or length. With a proper contactless energy transmission by shock wave to the micro sample, a stepwise electrohydraulic extrusion of micro samples would be enabled. With sheet metal free forming tests different pulse energies were used to investigate the controllability of the shock waves. Afterwards, the extrusion of micro samples was investigated. Here, the influence of the initial diameter on the deformation of spherical samples as well as the influence of varied pulse energies on the forming result were observed.

2 Testing set-up

In a pressure chamber filled with distilled water a short circuited aluminum (Al99,5) wire with a diameter of d_w = 300 µm and a length of l_w = 20 mm initiated the shock wave. The electric energy was provided by a capacitor bank with a capacity C = 100 µF. When the aluminum wire vaporized, the arising plasma caused a shock wave that traversed through the fluid and was used for forming. In the experiments the loading voltage of the capacitor bank was varied from U_0 = 1.2 kV to U_0 = 2.4 kV, Fig. 2.

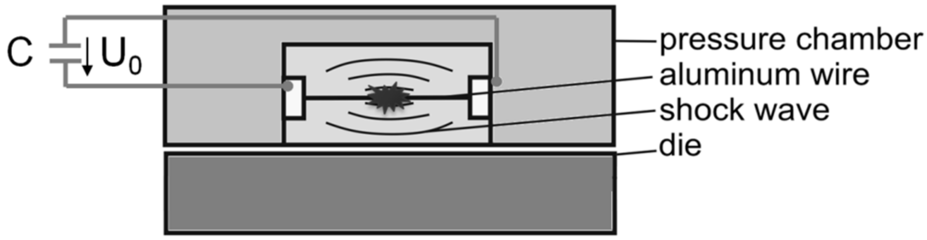

Figure 2: *Electrohydraulic shock wave set-up*

2.1 Free forming set-up

Free forming tests of sheet metals were performed to investigate the possibility of dosing the shock wave generation. Here, for different relative energies E_R the sheets with a thickness of s_0 = 1 mm deformed freely in the die and the resulting height h of the formed bulge was measured, Fig. 3. The relative energy E_R (**Eq. 1**) was varied from $E_R < 1$ to $E_R > 2$.

$$E_R = E_C/E_V \tag{1}$$

Afterwards the height was normalized to yield the relative forming height h_R, which was calculated by **Eq. 2**.

$$h_R = h(E_R)/h(E_R{=}1) \tag{2}$$

The energy for vaporization was calculated theoretically by the product of the approximate value of vaporization energy per kilogram (aluminum: 14 MJ/kg, (Löffler, 2001)) and the estimated volume V_w of the vaporized wire of about $V_w \approx 6$ mm³.

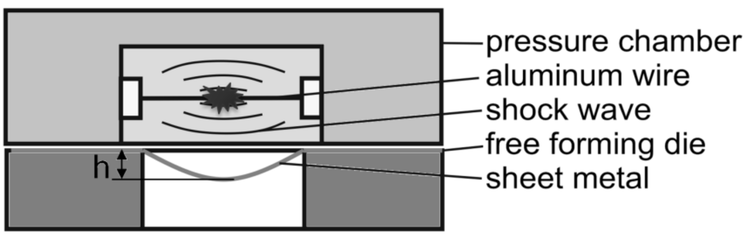

Figure 3: *Free forming set-up*

2.2 Electrohydraulic extrusion set-up

In the extrusion experiments spherical microscopic bronze (CuSn6) samples, that were generated by single droplet solidification with initial diameters between d_s = 550 µm and d_s = 650 µm, were extruded to a final diameter d_e = 500 µm of the extrusion die. The arising current pulse through the wire with the rise time t_R was measured with a Rogowski coil and the voltage at the capacitor bank was measured with a high voltage differential probe, Fig. 4. A first calibration pulse with E_{cal} = 276 J (E_R = 5.2) was used to settle the spherical sample in the die. Afterwards consecutive pulses were performed with E_{st} = 72 J (E_R = 1.3).

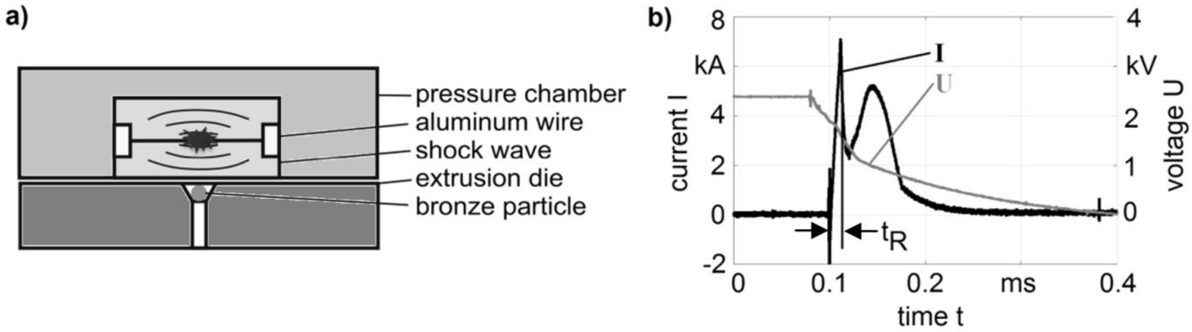

Figure 4: *Electrohydraulic extrusion set-up: a) cross-sectional view, b) typical current and voltage curve*

2.3 Deformation measurement set-up

In the current state, the extruded samples were scanned from above in the open die with a set-up based on a laser-line triangulation sensor, Fig. 5a. Moving the laser along the tool in y-direction with a high precision feed axis, 2D-profiles were stitched to a 3D-scan, Fig. 5b. The extrusion depth e (Fig. 5c) was measured as a coarse indicator for the progress of deformation after each extrusion step and the step size Δe was calculated with **Eq. 3**.

$$\Delta e_i = e_{i+1} - e_i \quad (3)$$

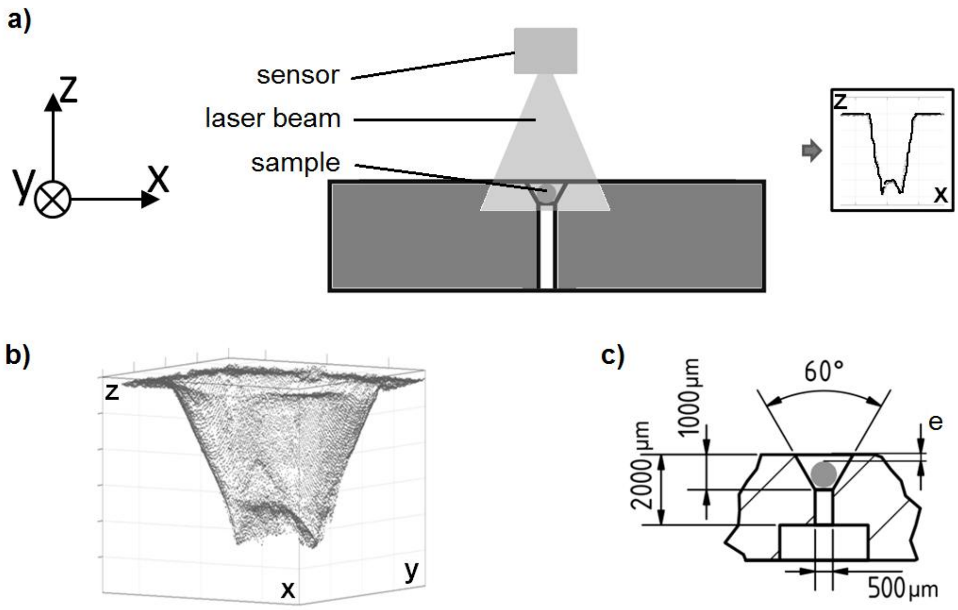

Figure 5: *3D-measurement: a) set-up, b) typical measurement, c) tool geometry*

To implement an enhanced side view measurement of the material flow behavior in multi-stage dies a feasibility study was performed. Bronze micro samples were pressed against a thick glass plate (d = 10 mm) and this arrangement was moved with a linear stage in front of a speckle measurement system. The applied movement of the whole sample surface simulates the deformations during the process, because they are observed as local movements of the surface. The measurement set-up for this study is shown in Fig. 6.

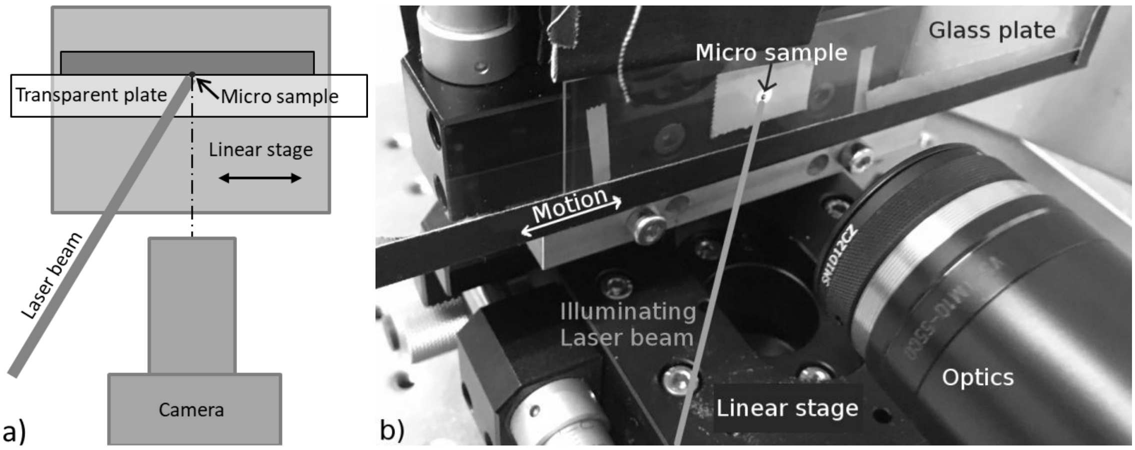

Figure 6: *Experimental set-up for the feasibility study for in-situ speckle pattern based measurements of the multi-stage material flow behavior: a) schematic drawing, b) photo of the measurement region with the micro sample and the additionally drawn laser beam*

3 Experiments and Results

3.1 Shock wave controlling

A sheet metal forming was reached even without a complete vaporization of the wire ($E_R < 1$) as a part of the wire stays solid. Increasing the relative energy E_R resulted in an increase of h_R with a complete vaporization. Increasing the energy, the vaporization time decreased, the current peak rise time t_R decreased, Fig. 7.

The change of action of the shock wave was caused by a faster discharge. However, with a lower ER the capacitor was not completely discharged. Nevertheless, even with low discharge energies small but sufficient forces could be generated.

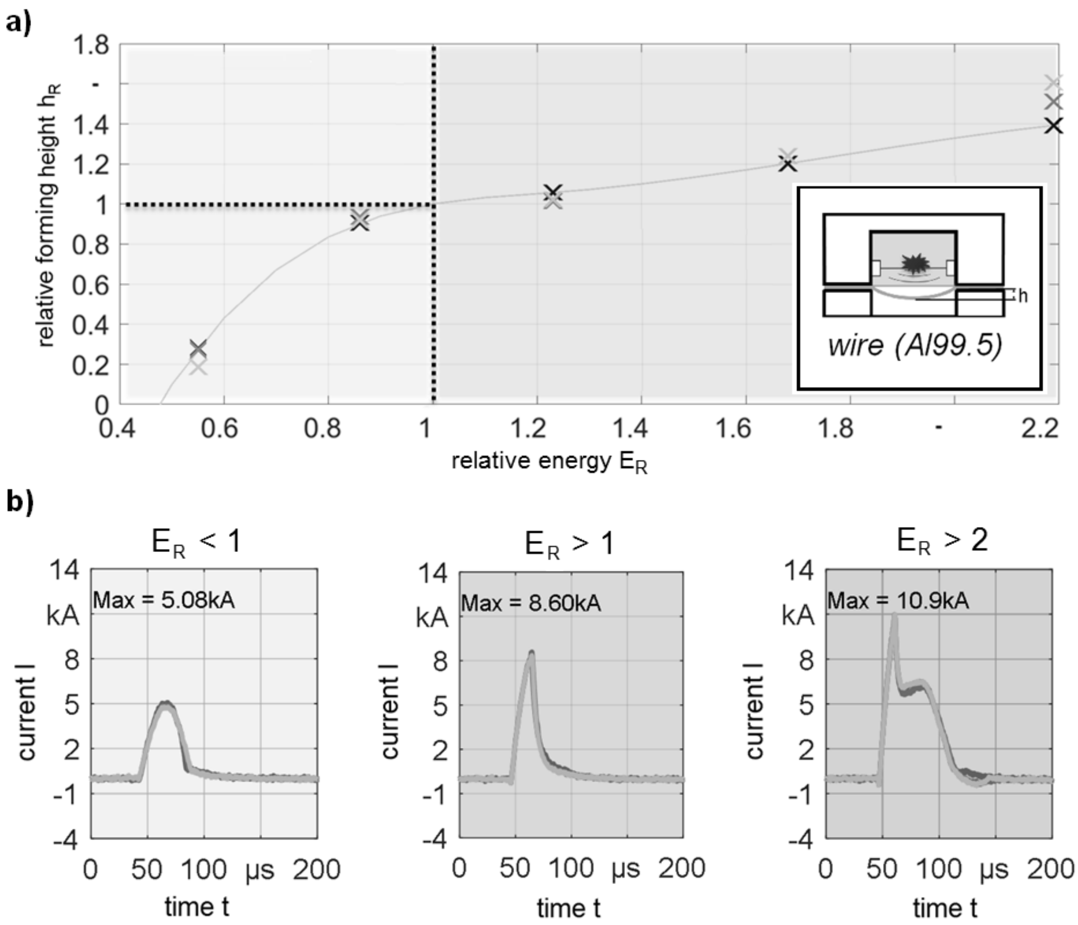

Figure 7: *Sheet metal forming with varying energy: a) relative forming height h_R as a function of the relative energy E_R, b) typical discharge characteristics*

3.2 Micro bulk forming

For the material testing by extrusion of micro samples different shock waves were applied. With the dosed shock waves, micro samples with different initial diameters were extruded. Increasing the energy ΣE (**Eq. 4**) by repeating the pulses with E_{st} = 72 J (E_R = 1.3) resulted in an increase of the extrusion depth e. The extrusion depth e as well as the incremental extrusion step size Δe varied with the samples diameter, Fig. 8. Sufficiently small steps sizes Δe < 100 µm could be realized.

$$\Sigma E = E_{cal} + \Sigma E_{sti} \tag{4}$$

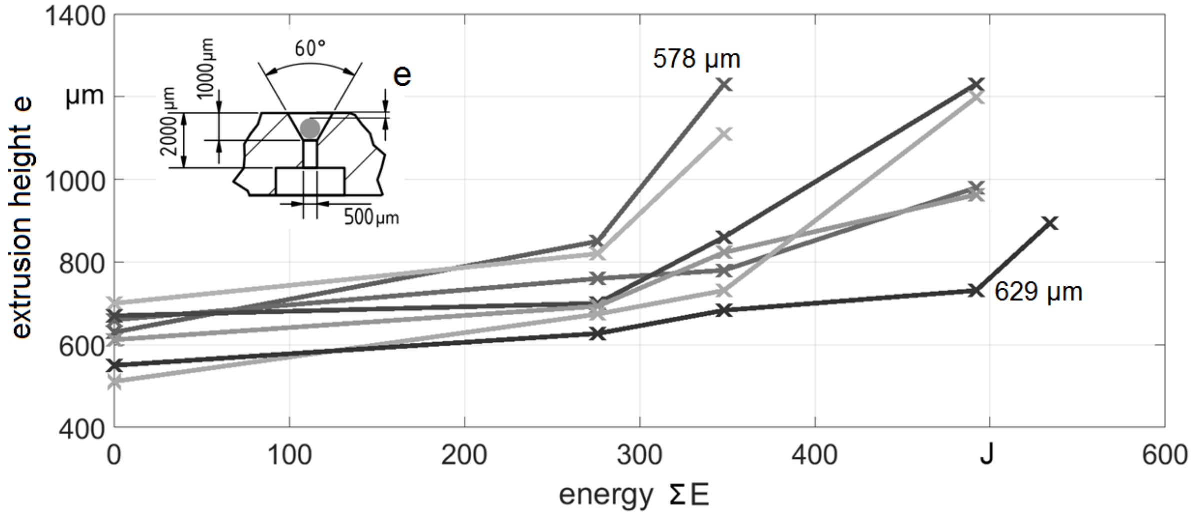

Figure 8: *Incremental extrusion of spherical samples with different initial diameters*

Due to the material flow of the diameter reduction the material tended to accumulate at the edge of the upper side (A), which can be seen by a burr, Fig. 9. Furthermore, still a sperical shape can be regognized at the upper side of sperical shape where the hydraulic punch was operating. This represents the ajustable shape of the hydraulic punch.

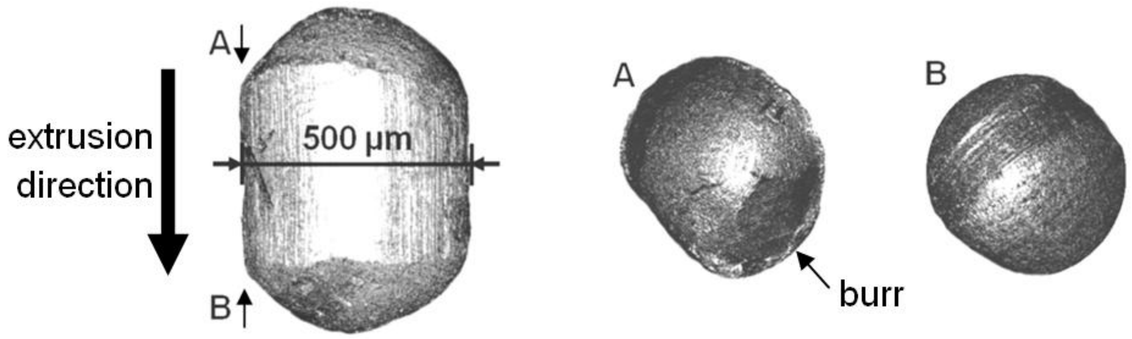

Figure 9: *Incremental deformed CuSn6 - spherical microscopic sample*

3.3 Speckle detectability and movement deviations

The experiments showed that speckle sizes in the optimal range of 2-6 pixels could be achieved depending on the aperture (f-number) of the used optics. Additionally, no significant deviations between the applied movements of the linear stage and the evaluated movements of the sample surface occurred for different illumination angles (inclination to the sample surface).

The resolution of the speckle photography method depends on several parameters like the speckle size, the magnification factor of the imaging system, the evaluation window size and the photon shot noise (Fischer, 2017; Tausendfreund, 2018). Estimations regarding the possible measurement setup showed, that a lateral resolution of ~10 µm and a deformation resolution of approximately 5 nm are feasible.

4 Conclusion

In this paper, spherical CuSn6 - micro samples with diameters between 550 µm and 650 µm were extruded incrementally by means of electrohydraulic forming. Hence, with the introduced set-up it was possible to transfer energy from the shock wave to the micro samples contactless. The stepwise extrusion was facilitated by properly controlled and dosed electrohydraulic shock waves by setting the relative energy E_R. With this incremental proceeding, the samples could be formed into deep cavities in small step sizes < 100 µm while measuring the sample geometry between the forming steps with a triangulation approach. Additionally, the feasibility of the speckle photography method for measurements of the sample surface deformation inside the forming die could be shown with laboratory tests, in order to increase the available information about the sample's forming behavior.

Future work will be addressed with the main objective of decreasing cycle times, fastening the measurement process, increasing the accuracy and investigating the characterization of materials for a high-throughput testing. The introduced laser-line triangulation measurement system will be enhanced by the space-resolved strain measurement system based on speckle photography, which will be applied in-situ within the pressure chamber and die assembly without the need to open them.

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