Influence of different process parameters on deformation velocity in laser shock forming*

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Abstract

In laser shock forming TEA-CO_2-laser induced shock waves are used to form metal foils, such as aluminum or copper. The process utilizes an initiated plasma shock wave on the target surface, which leads to a forming of the foil. 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 range of MPa can be achieved. In this article, the dependence of deformation velocity in laser shock forming on various materials as well as laser pulse intensities was determined experimentally for a laser shock bending process. In order to categorize these influences a theoretical model for deformation velocity based on the energy balance is proposed, which allows the evaluation of the influencing variables.

Keywords

High speed forming, Laser shock forming, Shock wave, Strain rate

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1 Introduction

Due to an ongoing trend towards function compaction, miniaturization becomes more and more important in industrial production. With increasing miniaturization, so-called scaling effects occur [1], which inhibit a further increase in miniaturization. However, scaling to smaller parts also enables the application of new processes. Such a new micro production process is the laser shock forming process, which operates as a high speed forming process based on TEA-CO_2-laser induced shock waves.

In former publications laser shock forming was already presented as a process which can be used for deep drawing of copper and aluminum foils [2]. For the forming process the pulsed laser focus is positioned on the specimen surface and creates a plasma which initiates a shock wave propagating into the material. This shock wave forms the sample. A more detailed process description of laser shock forming is already presented in various publications, i.e. [3] and [4]. The laser induced shock waves reach pressures in range of MPa with a pulse intensity of 0.8 GW/cm². In [2] it was determined, that the maximum of measured shock wave signal has a rise time of 5 µs. In this article, the influence of various laser pulse energies and various materials on the deformation velocity of laser shock forming is investigated for a single bending process. In order to categorize these influences a theoretical model for deformation velocity based on the energy balance is proposed. This model will allow the evaluation of the effect of the influencing parameters.

2 Methods

2.1 Experimental Set-Up

In this article, laser shock forming is applied to single bending in order to investigate the material behavior. Fig. 1 displays a sketch of the bending tool and the geometrical process parameters: bending angle α, bending radius R_N, sample overlap length x_L and focus position on the sample. The forming process was recorded by a high speed camera (Vision Research Phantom V 5.1) at a frame rate of 95000 fps and a resolution of 64 x 32 pixels in order to visualize and measure bending angle over time as a basis for calculating bending velocity over time. For bending angle, a 45° angle was chosen. For sample overlap length 5 mm was chosen. To determine an appropriate bending radius, the minimum formable radius was estimated. With a uniform elongation ε_u of 14 % for the used 50 µm thick Al99.5 foil, a lower boundary for the bending radius $R_{N,min}$ > 0.2 mm was calculated given by following formula, which is valid for small bending angles [5]

$$\varepsilon_{pl} = \ln(\varepsilon + 1) = \ln\left(\frac{\frac{s_0}{2}}{R_N + \frac{s_0}{2}} + 1 \right) \tag{1}$$

$$\Leftrightarrow R_{N,\min} > \frac{\frac{s_0}{2}}{e^{\varepsilon_u}} - \frac{s_0}{2}$$

where R_N is the drawing die radius, s_0 is the thickness of foil, ε_{pl} is the true strain and ε is the engineering strain. For manufacturing reasons a bending radius of 0.5 mm was used for the 45°-bending angle. The focus size was 2.6 mm x 2.6 mm. The focus centre is positioned at the end of the specimen (see Fig. 1) in order to ensure a uniform and highly reproducible movement of the strip. For determination of deformation velocity of various materials aluminum as well as copper in thicknesses of 20 µm and 50 µm with overlap lengths of 5 mm were investigated. In Fig. 2, the temporal evolution of a typical laser shock bending process is given. Tool environment in this assembly with laser pulse intensity of 0.8 GW/cm² relate to shock wave pressures of approximately 2.3 MPa according to our shock wave measurements. The video was taken at a sampling rate of 95.000 fps. It displays that bending angles can be determined very well.

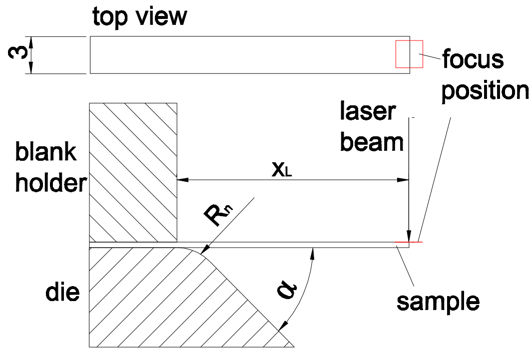

Fig. 1 Single bending tool for laser shock forming (x_L: sample overlap length, R_N: bending radius, α: bending angle)

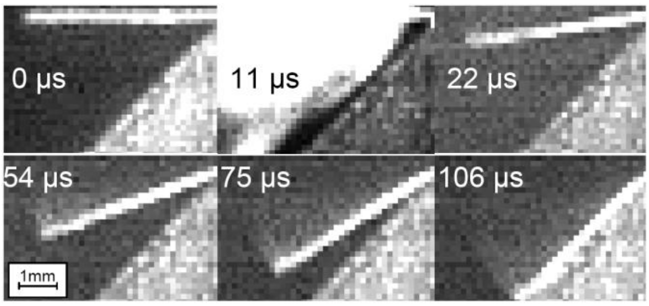

Fig. 2 Laser shock bending (laser pulse intensity: 0.8 GW/cm², pulse duration: 100 ns, laser focus size: 0.07 cm², shock wave pressure: 2.3 MPa, material: Al99.5, thickness 50 µm, overlap length x_L 5 mm)

2.2 Estimation of strain

In order to evaluate workpiece deformation velocity of laser shock bending, the bending angle was obtained from high speed video data. On the basis of a determination of the bending angle for each frame using image evaluation code, workpiece deformation velocity v_d was calculated using the temporally changing bending angle α.

The current workpiece deformation velocity v_d was calculated by virtual circular arc of specimen edge per second:

$$v_d = \frac{x_L \cdot \Delta\alpha}{\Delta t} \tag{2}$$

where x_L is the specimen overlap length, α is the bending angle and t is the time.

3 Model for deformation velocity

A theoretical model for deformation velocity is proposed in order to describe the dependency of the deformation velocity v_D on the material and the laser pulse energy. For this model, the energy balance of the bending process is made. By comparison with the experimental results, an efficiency factor c_{eff} for the laser pulse can be obtained, describing the proportion of effective laser pulse energy. The laser pulse energy E_{pulse} is mainly attributed to kinetic energy E_{kin}, bending energy E_{bend} and aerodynamic drag energy E_{cw}

$$c_{eff} \cdot E_{pulse} = E_{kin} + E_{bend} + E_{cw} \tag{3}$$

The kinetic energy E_{kin} of a strip with strip width *b*, thickness s_0, sample overlap length x_L and material density ρ is given by i.e. [6]

$$\begin{aligned} E_{kin} &= \frac{1}{2}\int_0^{x_L} \rho b s_0 v^2 dx_L = \frac{1}{2}\int_0^{x_L} \rho b s_0 (x_L\dot{\alpha})^2 dx_L = \frac{1}{2}\rho b s_0 \dot{\alpha}^2 \frac{x_L^{\;3}}{3} \\ \Leftrightarrow E_{kin} &= \frac{1}{6}\rho b s_0\, v^2 x_L \end{aligned} \tag{4}$$

The bending energy of the single bending process is given by the acting moment M at the shock wave application point (i.e. the focus point of the laser spot) over the bending angle α. Thus, with the given true stress $k_f(\varepsilon_{pl})$ and a bending angle α, the bending energy E_{bend} is given by [7]

$$E_{bend} = \int_0^{\alpha} M d\alpha = \frac{1}{4} \cdot k_f(\varepsilon_{pl}) \cdot b s_0^2 \alpha \tag{5},$$

where true strain ε_{pl} is calculated out of formula (1).
Finally, the aerodynamic energy E_{cw} of the strip with aerodynamic drag c_w can be written as [6]

$$\begin{aligned} E_{cw} &= F_{cw} \cdot s = \frac{1}{2}\int_0^{x_L} c_w b \rho_L x_L (x_L\dot{\alpha})^2 dx_L \\ \Leftrightarrow E_{cw} &= \frac{1}{8} c_w b \rho_L v^2 x_L^{\;2} \end{aligned} \tag{6}$$

with density of air ρ_L.
Thus, for the velocity v_E of the end of the strip we find

$$v_E = \sqrt{\frac{c_{eff} \cdot E_{pulse} - \frac{1}{4} \cdot k_f(\varepsilon_{pl}) \cdot bs_0^2 \alpha}{\frac{1}{6}\rho b s_0 x_L + \frac{1}{8} c_w b \rho_L {x_L}^2}} \tag{7}$$

4 Experimental Results

4.1 Influence of specimen material on deformation velocity

Fig. 3 illustrates the time-related characteristics of bending angle for different materials. It is obvious that the bending velocity is quite constant for aluminum 20 µm and 50 µm as well as for copper 20 µm over the whole bending process. Only for copper 50 µm, the 45° bending angle was not be achieved, and a decrease of deformation velocity was observed. As an assumption, a deformation velocity v_D independent of time can be obtained for the specimens aluminum 20 µm, aluminum 50 µm and copper 20 µm as slope of a linear data fit. For the specimens copper 50 µm a deformation velocity v_D independent of time can be obtained by the same linear approximation up to the bending angle of 15°.

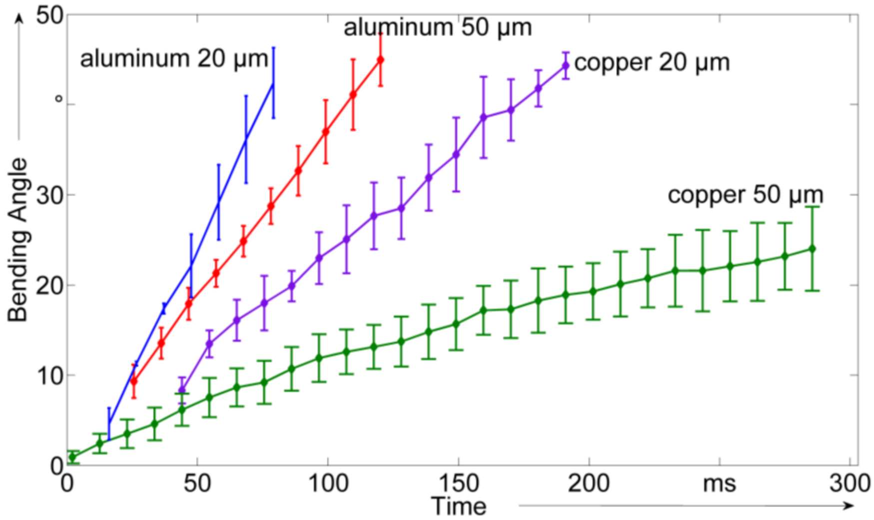

Fig. 3 Bending angle versus time for Al99.5 and copper with thicknesses 20 µm and 50 µm (pulse intensity: 0.8 GW/cm²; shock wave pressure: 2.3 MPa; x_L = 5 mm)

Fig. 4 displays the deformation velocity approximated accordingly by linear fit for all materials and thicknesses investigated. Velocities between 8.5 and 48 m/s were reached. It can be inferred that with increasing foil thickness the deformation velocity decreases. Furthermore, as expected, the deformation velocity is material-dependent and decreases with increasing density and yield stress.

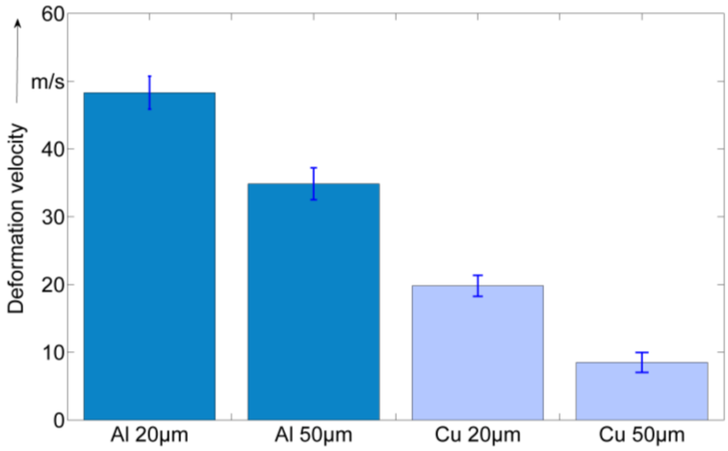

Fig. 4 Deformation velocities for Al99.5 and Cu with thicknesses 20 µm and 50 µm (pulse intensity: 0.8 GW/cm²; shock wave pressure: 2.3 MPa; x_L = 5 mm); for copper 50 µm linear approximation up to bending angle of 15°

4.2 Influence of pulse energy and pulse intensity on deformation velocity

In order to determine the influence of pulse energy and pulse intensity on deformation velocity, aluminum and copper specimens with thickness of 50 µm and overlap lengths of 5 mm were applied with different pulse energies and deformation velocities were determined. Fig. 6 and Fig. 7 display the results for aluminum and copper specimens. The copper specimens reached not more than 3° bending angle for the lowest laser pulse energy. Furthermore, the deformation velocities were not constant over time for copper 50 µm specimens (see Fig. 3). Thus, the mean deformation velocity was calculated for all laser pulse energy steps between 0 and 3° bending angle. In case of aluminum and copper, an obvious decrease of deformation velocity with decreasing pulse energy and intensity was observed.

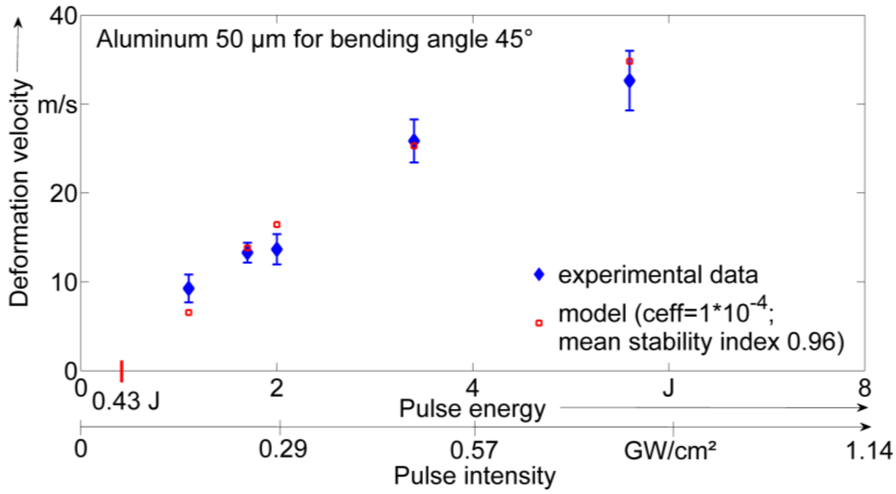

Fig. 5 Experimental and theoretical results of deformation velocity at various laser pulse energies for 50 µm thick Al-sample (shock wave pressure: up to 2.3 MPa; x_L = 5 mm)

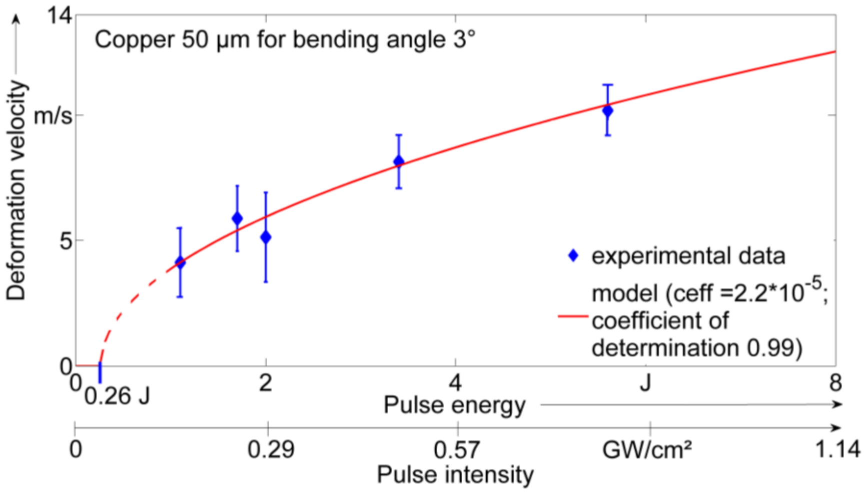

Fig. 6 Experimental and theoretical results of deformation velocity at various laser pulse energies for 50 µm thick Cu-sample (shock wave pressure: up to 2.3 MPa; x_L = 5 mm)

5 Comparison of experimental results and theoretical model

In order to describe the influence of laser pulse energy and the material on the deformation velocity, the base model in section 3 based on the energy balance of the process was used. A closer view on the contribution of the components of the energy balance for the exemplary case of an Al99.5 foil with a thickness 50 µm and various laser pulse intensities investigated in this study is given in Fig. 7. This illustrates that for higher energy the kinetic energy is 0.3 mJ (75 %) higher than the other energies. By decreasing laser pulse energy, an approximation of kinetic and bending energy is observable.

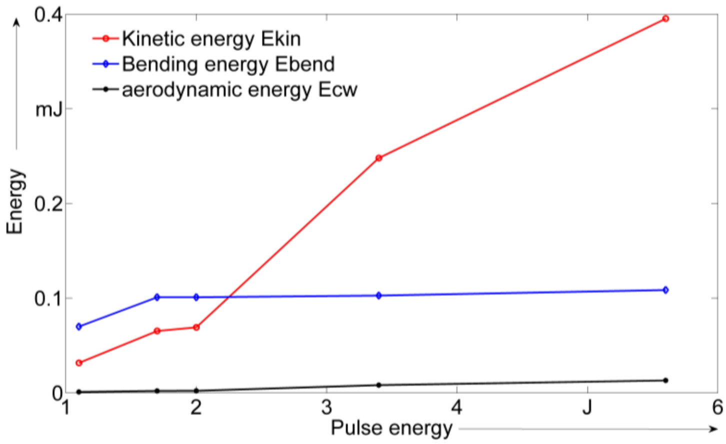

Fig. 7 Calculated kinetic, bending and aerodynamic energy versus pulse energy for aluminium foil with a thickness of 50 µm

The efficiency factor c_{eff} was fitted on the basis of all experimental data for various laser pulse energies depending on the respective material. The resulting values for c_{eff} are $1 \cdot 10^{-4}$ for 45° bending of aluminum, $5.5 \cdot 10^{-5}$ for 3° bending of aluminum and $2.2 \cdot 10^{-5}$ for 3° bending of copper. Besides of the material, the efficiency factor depends on the spatial restriction on the shock wave (change in effective pressure on the specimen) i.e. by the tool and the bending angle. Earlier estimations of the process efficiency by means of pressure measurements for stretch forming using a blank holder amounted to $6 \cdot 10^{-4}$ to $7 \cdot 10^{-4}$ for aluminum 50 µm [8]. This shows that the pressure wave is more effective in forming a circular specimen surrounded by a blank holder than in bending without any restriction on the spatial propagation of the shock wave.

For comparison of experimental data and theoretical model in Fig. 5 and Fig. 6 the material-dependent efficiency factors of $1 \cdot 10^{-4}$ for 45° bending of aluminum and $2.2 \cdot 10^{-5}$ for 3° bending of copper, measured true strain $k_f(\varepsilon_{pl})$ and material density ρ from literature were taken. True strain was calculated based on the realized bending radius. The results in Fig. 5 and Fig. 6 illustrate a good correlation with coefficient of determination of 0.96 for aluminum and 0.99 for copper. Thus, the significant decrease of deformation velocity with decreasing laser pulse energy can be properly described by the energy balance incorporating kinetic energy, bending energy and aerodynamic energy.

Furthermore, it is obvious that laser pulse energy of 0.43 J is the theoretical lower limit required for plastic bending of 45° for aluminum 50 µm in this set-up. It is a theoretical value, since laser shock forming causes high speed forming and this always integrates kinetic and aerodynamic energy. For plastic bending of 3° of copper 50 µm, a laser pulse energy of 0.29 J is calculated as the required lower energy limit with the set-up and tooling used.

In Fig. 8 the experimentally determined deformation velocities for the materials from Fig. 4 are compared to the deformation velocities predicted by the model. The model for copper is calculated with angle of 3°, with the efficiency factor determined for bending of copper of 3°. The tolerance markers at the model bars indicate the sensitivity of the calculated deformation velocity taking into account the uncertainty of the model parameters yield stress k_f and material density ρ. Based on our measurements for the yield stress k_f a variation up to 13 %, for the true stress $k_f(\varepsilon_{pl})$ a variation up to 8 % and for the material density ρ an assumed variation of 5 % was used for the sensitivity analysis. This sensitivity analysis Δv_E showed that the material density has a bigger influence on the deformation velocity than the yield stress of the material:

$$\Delta v_E = \sqrt{10^{-15} \Delta k_f{}^2 + 10^{-5} \Delta \rho^2} \tag{10}$$

The comparison of experiment and model in Fig. 8 displays a good correlation for the 50 µm thick aluminum and copper specimens. The comparison of experiment and model for the 20 µm thick copper samples demonstrates less correlation, which is not clarified yet. However, the range of the deformation velocity matched quite well with experimental results.

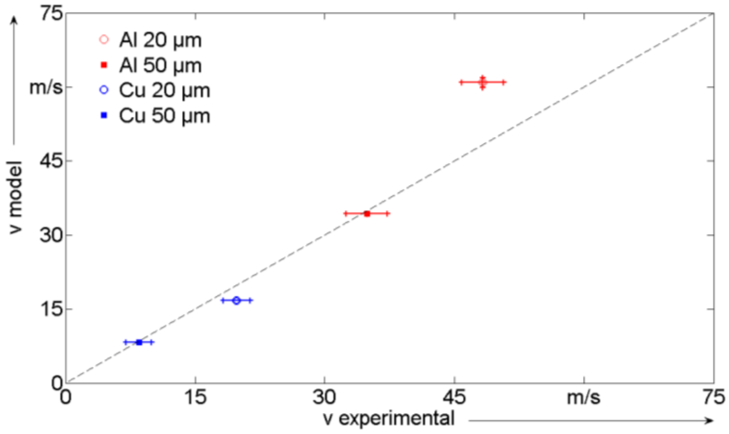

Fig. 8 Deformation velocities from theoretical model vs. deformation velocities from experimental data for Al99.5 and Cu with thicknesses 20 µm and 50 µm (pulse intensity: 0.8 GW/cm²; shock wave pressure: 2.3 MPa; x_L = 5 mm)

6 Conclusions

The dependence between deformation velocity of laser shock bending and laser pulse intensity was determined experimentally and investigated by a theoretical model based on the energy balance incorporating kinetic energy, bending energy and aerodynamic energy. It was established that the kinetic energy is up to 75 % higher in high energy case, and therefore it has a larger influence than the other energies. The efficiency factor c_{eff} was estimated depending on the respective material. The resulting values are $c_{eff} = 1{\cdot}10^{-4}$ for 45° bending of aluminum and $c_{eff} = 2.2{\cdot}10^{-5}$ for 3° bending of copper with a laser pulse intensity of 0.8 GW/cm² (shock wave pressure: 2.3 MPa). The model showed a good correlation for single bending with a shock wave, which is initiated in an open environment without any surrounding tool. The theoretical minimum laser pulse energy for plastic bending by laser shock bending was determined by the model.

References

[1] *Vollertsen, F.:* Categories of size effects, Production Engineering - Research and Development, Volume 2, Number 4, 2008, p. 377-383

[2] *Wielage, H.; Schulze Niehoff, H.; Vollertsen, F.:* Forming Behaviour in Laser Shock Deep Drawing, International Conference on High Speed Forming 2008, ICHSF 2008, Proceedings, Universität Dortmund, Institut für Umformtechnik und Leichtbau, Dortmund, Germany, March 11-12 2008, p. 213-222

[3] *Vollertsen, F.; Schulze Niehoff, H.; Wielage, H.:* On the acting pressure in laser deep drawing, Production Engineering - Research and Development, Volume 3, Number 1, Springer-Verlag, Berlin/Heidelberg, März 2009, p. 1 – 8

[4] Schulze Niehoff, H.; Hu, Z.; Vollertsen, F.: Mechanical and Laser Micro Deep Drawing, SheMet 2007, Trans Tech Publications, CH-Zürich, 2007, p. 799-806

[5] *Doege, E.; Behrens, B.-A.:* Handbuch der Umformtechnik – Grundlagen, Technologien, Maschinen, Berlin, Springer, 2007, p. 56

[6] *Beitz, W. (Hrsg.) ; Grote, K.-H. (Hrsg.)*: Dubbel : Taschenbuch für den Maschinenbau, 20. Aufl. Berlin, Springer, 2000

[7] *Lange, K. (Hrsg.):* Umformtechnik – Handbuch für Industrie und Wissenschaft, Band 3: Blechbearbeitung, Springer-Verlag, 1990

[8] *Wielage, H.; Vollertsen, F.:* Investigations of forming Behaviour in Laser Shock Deep Drawing, steel research international 80, No. 5, Düsseldorf, 2009, p. 323 -328