Journal for Technology of Plasticity, Vol. 32 (2007), Number 1-2

ON THE DRAWING LIMIT IN MICRO DEEP DRAWING

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ABSTRACT

Micro deep drawing becomes a more and more industrial relevant process. But due to size effects new challenges are involved in this process compared to macro deep drawing. The size effects cause an increase of friction and thus hinder the material flow. Therefore the limit drawing ratio in micro deep drawing becomes smaller than that in macro forming. The effect of changes concerning friction and flow behavior on drawing limit in micro deep drawing is subject of the presented investigations in this paper. Scaled deep drawing experiments were carried out with five different punch diameters, whereby the tribological size effects were observed: the friction coefficient between workpiece and tools increases if the process dimension decreases.

Key words: *micro deep drawing, limit drawing ratio*

1. INTRODUCTION

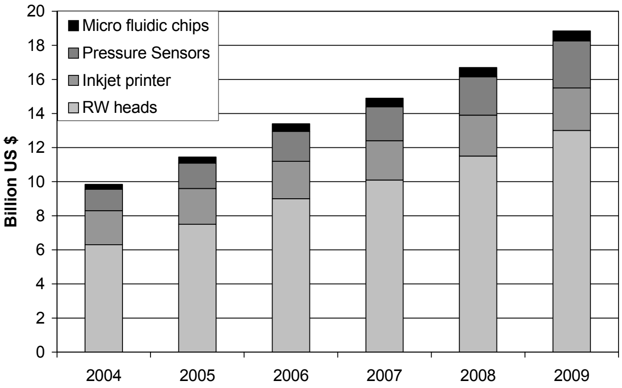


Fig.1 - Estimated market for selected MST and MEMS products with micro formed components[1]

Micro formed parts are often components of micro system technologies (MST) or micro electro-mechanical systems (MEMS), especially read and write heads, inkjet devices, pressure sensors and micro fluidic chips. They contain leverages, connector pins, resistor caps, contact springs and chip lead frames [2]. The estimated rise in turnover from 10 to 19 billion US $ from 2004 until 2009 [1] shows a growing demand on micro formed parts, which is mainly driven by a rising trend of miniaturization, see Fig. 1. Thus, investigation and improvement of micro forming processes are needed.

2. EXPERIMENTAL CONDITIONS

Deep drawing experiments with 5 different punch diameters (1, 5, 10, 20 and 50 mm) were carried out with consideration of the law of similarity [3]. All geometrical parameters of tools and work pieces are scaled by the same scaling factor, for example the ratio of work piece thickness to punch diameter is kept the same. All process parameters are constant for all experiments, i. e. the work piece materials and the surface quality of the tools etc. This procedure can cause unexpected results, since size effects are documented for different parameters: The flow curve, the deviation of the flow curve and the friction change along with miniaturization [4].
Al99.5 is used as work piece material in every process dimension. Regarding that, the flow behaviours of the material are also affected by the size effects [5, 6, 7], Al99.5 in different thicknesses can not have the same flow curves. For the determination of the forming force in this investigation the flow stress is required. Thus, the tensile tests were carried out to acquire the flow curves of Al99.5 in each thickness and taken into account, see Fig. 2.

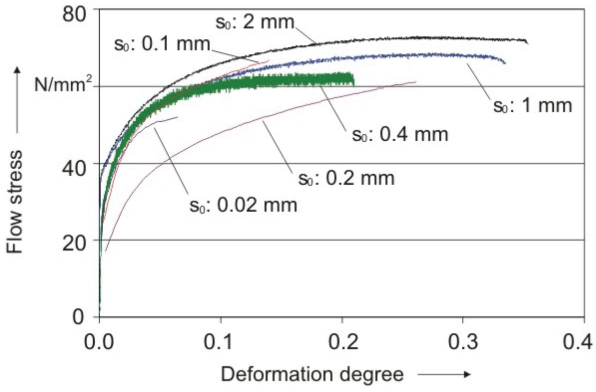


Fig. 2 - Flow curves of Al99.5 in different thicknesses

Experiments were carried out on a double-axis extreme dynamic micro forming press, which was developed in BIAS. It is driven by electrical linear motors with a maximum acceleration of 17 g and a maximum velocity of 3.2 m/s. The positioning error of this press is under 3 µm at maximum acceleration. The repeat positioning error of this press is under 1 µm up to a stroke of 8 mm.
The experimental setups were installed on the micro forming press including a force measurement system with an accuracy of 0.01 N and a position measurement system with an accuracy of 0.003 mm. We thus get the punch force/punch travel-curve, which can in future work be used for the calculation for friction coefficients in deep drawing processes.

3. PARAMETER IDENTIFICATION METHOD

In former investigations strip drawing was used to determine size effects of friction in sheet metal forming, see Fig. 3 a). Therefore a friction function f(μ) could be calculated from the process parameters and the punch force/punch travel-curve and showed that the friction in strip drawing increases significantly, if the process is miniaturized [8]. The strip drawing was a simplification of the deep drawing process, since the tangential force F_t was excluded, see Fig. 3 b).

Now, scaled deep drawing was carried out. Tribological size effects can already be observed by the punch force/punch travel-curve, if the punch force is normalized by the punch diameter d, the sheet thickness s_0 and the flow stress k_f.

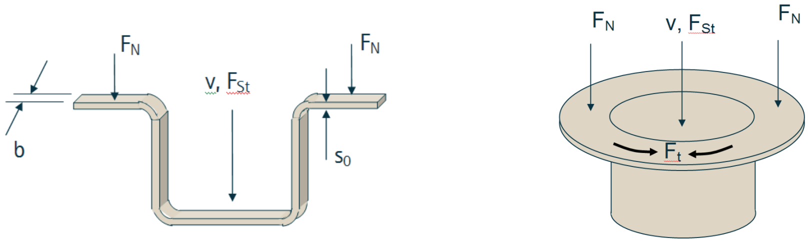


Fig. 3: a) Strip drawing *b) deep drawing*

Storoschew [9] showed, that the maximum punch force F_{max} in deep drawing can be evaluated by:

$$F_{\max} = \pi d s_0 \sigma_{Qg\max} \tag{1}$$

Whereby

$$\sigma_{Qg\max} = k_f \left(\ln\frac{D}{d} + \frac{2\mu F_N}{\pi D s_0 k_f} + \frac{s_0}{2r_Z + s_0} \right) \cdot (1 + 1.6\mu) \tag{2}$$

where are:

d: punch diameter
s_0: original thickness
D: initial blank diameter
F_N: blankholder force
k_f: flow stress
r_Z: drawing radius and
μ: friction coefficient.

Equation (1) and (2) give thus

$$\frac{F_{\max}}{k_f d s_0} = \pi \left(\ln\frac{D}{d} + \frac{s_0}{2r_Z + s_0} \right)(1 + 1.6\mu) + \frac{2\mu F_N}{D s_0 k_f}(1 + 1.6\mu) \tag{3}$$

In all experiments D/d was held constant. The same applies for $s_0/(2r_z+s_0)$. It can thus be written that

$$\frac{F_{\max}}{k_f d s_0} = \pi(C_1 + C_2)(1 + 1.6\mu) + \frac{2\mu F_N}{D s_0 k_f}(1 + 1.6\mu) \tag{4}$$

whereby C_1 and C_2 are constants. This shows that differences of the maximum punch force are only due to friction and flow stress, if it is normalized. Within this work the value μ in equ. (4) is called effective average coefficient of friction, as it is an average of the friction coefficient acting at different areas of the workpiece-tool interface under different contact pressures. These different contact pressures were accounted for by the strip drawing test procedure described elsewhere [8]. Further work will be done to account for that also in deep drawing.

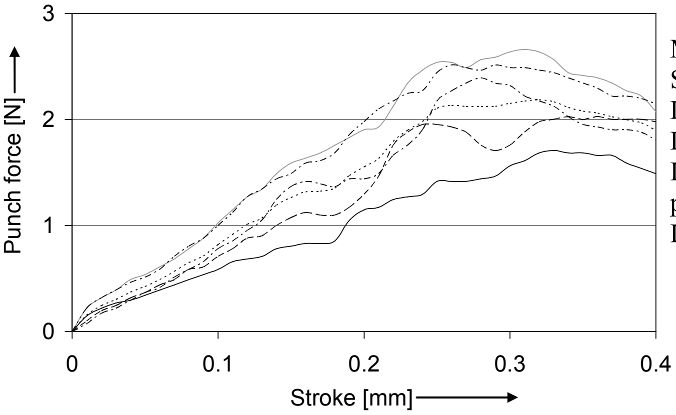
In our previous investigations [10, 11] the friction functions were acquired from scaled strip drawing tests. The friction functions describe a dependence of the friction coefficient on normal contact pressure. Using our method the friction functions were calculated from the whole punch force vs. stroke curve instead of only one punch force point like in theory of Storoschew. This calculation method has two advantages in comparison to the theory of Storoschew:

- The change of normal contact pressure is taken into account. Since the friction coefficient depends on the normal contact pressure [12, 13], which varies in a relative big range within deep drawing process, it is meaningful to take the change of normal contact pressure into account for calculation of friction coefficient. Thus the calculated friction coefficient using the theory of Storoschew is valid only at the point of maximum punch force.
- Some other works [14] took also different friction coefficients for radius of die and flange into account in their equation, but they are usually assumed to be constant during the process. Thus it is impossible to calculate the punch force or friction coefficients precisely using their equations. In our work the friction coefficients at the radius of die and at the flange are considered respectively. The normal contact pressures at the radius of die and at the flange can not be always the same. As mentioned above, the friction coefficient is affected by the normal contact pressure, so that the friction coefficient at the radius of die and at the flange should differ from each other, since they are subjected to different normal contact pressure.

Since the tangential force and the resulted forming at flange in deep drawing was excluded in the calculation method for strip drawing, this method can not be directly used to calculate the friction functions for deep drawing. Using the theory of Storoschew only the effective average friction coefficient can be acquired from the maximum punch force, which can not be used to analyze the friction behavior in the whole deep drawing process. But the effective average friction coefficients from different punch diameters can show a changing trend in dependence on the punch diameter, which indicates the tribological size effects. Thus the theory of Storoschew was used in this work. In our future work this calculation method for strip drawing will be extended to deep drawing.

4. RESULTS

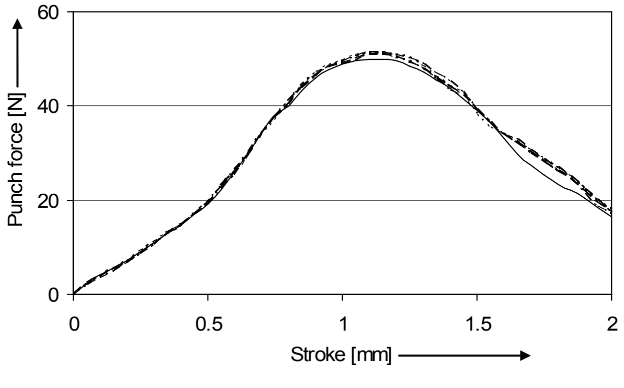
The experimental investigations in micro deep drawing were carried out in order to expand the investigations in strip drawing to deep drawing. The results show, that the scatter of measured parameters is comparable high in micro deep drawing. Fig. 3 shows 6 punch force/punch travel-curves for the same micro cup deep drawing process with a punch diameter of 1 mm. It can be seen that the maximum punch force ranges from 1.7 to 2.7 N, which corresponds to a deviation of 37 %. Thus, the 6 curves are averaged to one curve for further investigations.



Material:	Al 99.5
Sheet thickness:	20 µm
Drawing ratio:	1.5
Drawing radius:	0.12 mm
Initial blank holder pressure:	0.5 N/mm²
Lubrication:	4 g/m²

Fig. 3 - Deviation of the punch force in deep drawing with 1 mm punch diameter

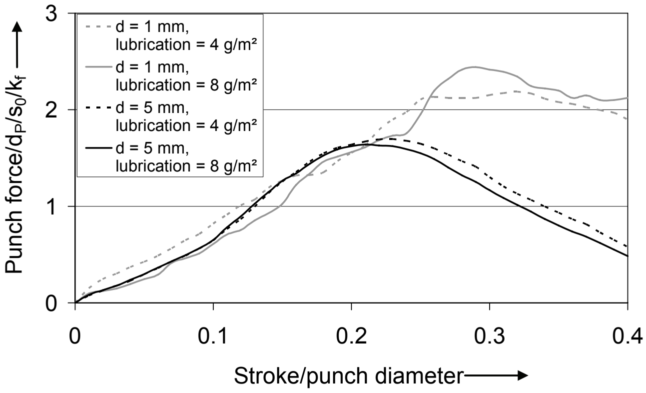
In contradiction to this, the punch force/punch travel-curves of the cup deep drawing process with a punch diameter of 5 mm show much lower scatter, see Fig. 4. The maximum of the 6 curves range from 50 to 52 N, which corresponds to a scatter of only 3.8 %. This shows that an increase of factor 10 in deviation by miniaturization of the deep drawing process.



Material:	Al 99.5
Sheet thickness:	100 µm
Drawing ratio:	1.5
Drawing radius:	0.6 mm
Initial blank holder pressure:	0.5 N/mm²
Lubrication:	4 g/m²

Fig. 4 - Deviation of the punch force in deep drawing with 5 mm punch diameter

If the punch force is normalized by the diameter of the punch, the sheet thickness and the flow stress ($F_P/(ds_0k_f)$) and if the punch travel is normalized by the punch diameter (s_P/d), then differences in friction can be observed, see Fig. 5. The normalized punch force of the micro deep drawing process with 1 mm punch diameter is 30-50 % higher than for the process with 5 mm punch diameter, which means that the friction increases with miniaturisation. The proportion of the micro friction coefficient to the macro friction coefficient μ_{micro}/μ_{macro} can be assessed by Eq. 4 to more than 2, which corresponds to the result from strip drawing. It can also be seen that the punch force increases, if the lubrication decreases from 8 to 4 g/m² with a punch diameter of 5 mm. This effect cannot be detected for the micro deep drawing process with a punch diameter of 1 mm, where the two curves are inconsistent and support the assumption that the amount of lubrication in micro sheet metal forming does not have the impact as in macro forming as it was observed in former investigations in strip drawing.



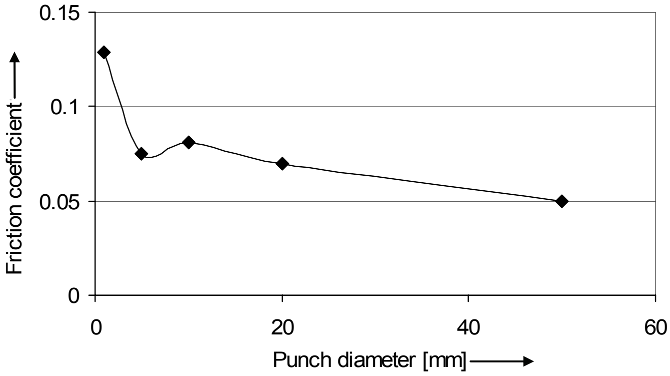
Material:	Al 99.5
s_0/d:	0.02
Drawing ratio:	1.5
Drawing radius:	0.12 x d
Initial blank holder pressure:	0.5 N/mm²
d:	punch diameter
s_0:	sheet thickness
k_f:	flow stress

Fig. 5 - Size effects in deep drawing

Scaled deep drawing with 5 different punch diameters were carried out using the same work piece material and lubricant. The process parameters are shown in Table 1. A summary of the size dependent friction coefficients in cup deep drawing derived by equation (1) and (2) are given in Fig. 6. They are in average 0.129 for punch diameter of 1 mm, 0.075 for punch diameter of 5 mm and 0.081 for punch diameter of 10 mm. These friction coefficients show that if the process dimension decreases, the friction increases.

Table 1 - Process parameter of the scaled deep drawing

Punch diameter [mm]	Blank thickness [mm]	Blank diameter [mm]	Drawn clearance [mm]	Drawn radius [mm]
1	0.02	1.5	0.028	0.12
5	0.1	7.5	0.14	0.6
10	0.2	15	0.28	1.2
20	0.4	30	0.56	2.4
50	1	75	1.4	6

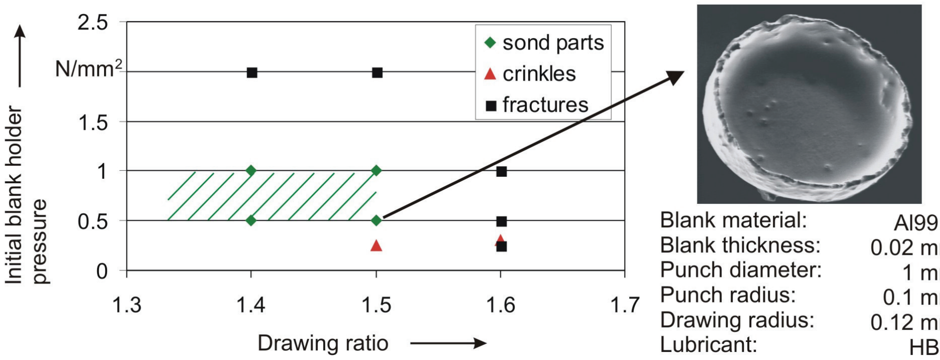


Drawing ratio:	1.5
Material:	Al99.5
Sheet thickness/punch diameter:	0.02
Initial blank holder pressure:	0.5 N/mm²
Lubricant:	HBO
Viscosity:	400 mm²/s
Lubricant amount:	4 g/m²
# of experiments/ point:	7

Fig. 6 - Size dependent friction coefficient (determined by use of the Storoschew) equation in mechanical deep drawing

The limit drawing ratio (LDR) is a characterising indicator for the deep drawing process. It shows how much the work piece material can be deformed in this process. The bigger the LDR is, the more the material can be deformed, and thus the more widely this process can be applied in industry. LDR is usually affected by the geometry of the tools and the work piece materials.

Micro deep drawing with punch diameter of 1 mm was carried out to investigate the LDR considering the size effects on LDR. The work piece out of Al99.5 in thickness of 0.02 mm was used. Constant blank holder force was applied in this investigation. As lubricant the oil HBO was used. A limit drawing ratio of 1.5 was acquired, see Fig. 7. Under the same forming condition and scaled tools geometry the limit drawing ratio of more than 1.8 can be reached in macro deep drawing with punch diameter of 50 mm. The LDR in macro deep drawing is clearly bigger than that in micro forming.



Blank material:	Al99.5
Blank thickness:	0.02 mm
Punch diameter:	1 mm
Punch radius:	0.1 mm
Drawing radius:	0.12 mm
Lubricant:	HBO

Fig. 7 - Process window of Al99.5 with punch diameter of 1 mm

5. DISCUSSION

Sound parts can be acquired only if the max. punch force does not reach the punch force by bottom fracture. The force by bottom fracture can be theoretically calculated by the following equation:

$$F_{BF} = \pi \cdot R_m \cdot d_m \cdot s \ , \tag{5}$$

whereby

R_m : tensile strength

d_m : middle diameter of cup wall

s : thickness of the work piece.

Theoretically the LDR can be achieved if

$$F_{BF} = F_{\max} \ . \tag{6}$$

Let

$$f(x) = \frac{F_{\max}}{F_{BF}} \ . \tag{7}$$

Equation (1), (2), (5) and (7) give thus

$$f(x) = \frac{\pi d s_0 k_f \left(\ln \frac{D}{d} + \frac{2\mu F_N}{\pi D s_0 k_f} + \frac{s_0}{2r_Z + s_0} \right) \cdot (1 + 1.6\mu)}{\pi \cdot R_m \cdot d_m \cdot s} \tag{8}$$

whereby

d: punch diameter
s_0: original thickness
D: initial blank diameter
F_N: blankholder force
k_f: flow stress
r_Z: drawing radius and
μ: friction coefficient.

Since $R_m \approx k_f$ and $d_m \approx d$, equation (8) can be written as

$$f(x) = \left(\ln \frac{D}{d} + \frac{2\mu F_N}{\pi D s_0 k_f} + \frac{s_0}{2r_Z + s_0} \right) \cdot (1 + 1.6\mu) \tag{9}$$

According to equation (5) and (9), the flow curve of the material and the friction coefficient show both an effect on the LDR. Firstly, the flow behaviour of the work piece material changes as the thickness of material changes. The flow curves of Al99.5 in different thicknesses show clearly size effects, i.e. the flow curve of the thinner material is lower and the equivalent strain of the thinner material is smaller, see Fig. 2. Similar Results were also acquired by Messner and Kals [5, 6]. According to equation (5) a lower tensile stress results in a lower bottom fracture force F_{BF}, which leads to a lower LDR. At the same time, a lower equivalent strain means a lower formability for the material, which can lead to a lower LDR too.

On the investigation reported here $F_{\max} < F_{BF,theo}$ (calculated by equation (5)) was observed. The reason for that is assumed to be the local geometric adaption between punch and blank, which results in a local strain, see Fig. 8 a). Concerning the size effects on flow curves, i.e. a smaller breaking elongation for the thinner blank, the necessary local strain can not be reached (See Fig. 8 b)), thus disruption occurs locally in micro deep drawing. While the assumption $F_{BF} = F_{\max}$ is based on a homogeneous strain and failure of the whole bottom, it might occur in micro deep drawing that the fracture limit is exceeded locally by an inhomogeneous adaption strain, induced at the beginning of the process. Therefore, $F_{\max}$ can not reach F_{BF} in micro deep drawing. As a result the LDR is smaller than predicted from $F_{BF,theo} = F_{\max}$. This effect is called “local flow behaviour effect”

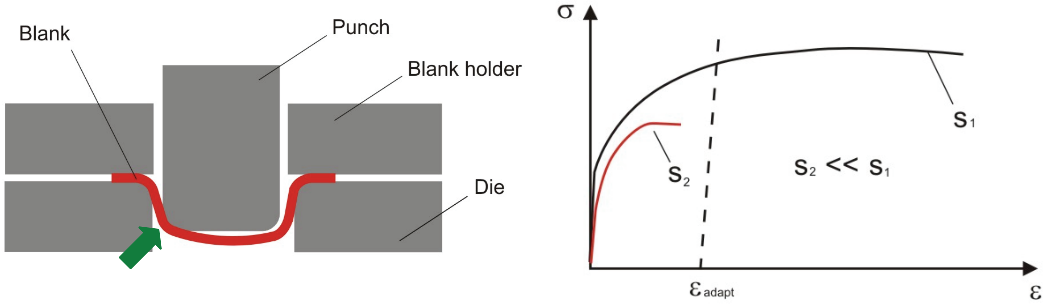


Fig. 8 - a) Local adaption in micro deep drawing *b) Flow stress vs. sheet thickness*

Moreover, tribological size effects can affect the limit drawing ratio. Experimental investigations show that the friction coefficient increases when the punch diameter or blank thickness decreases. As mentioned in chapter 4, using the theory of Storoshew the friction coefficient was calculated from the max. punch forces, they are 0.05 for punch diameter of 50 mm and 0.129 for punch diameter of 1 mm.

The reduction of the LDR by the change of friction behaviour can be estimated as follows. At the macro level (d=50 mm), the coefficient of friction is 0.05. In the micro range we got μ=0.129 with an LDR of 1.5. If $f(x)$ in equation (9) is constant and the friction coefficient in the micro range would decrease to that of the macro level, e.g. 0.05, one could allow a bigger blank diameter, which would result in LDR=1.6. This effect is called “tribological effect”. A third effect is due to the flow stress influence on the second sum term in equation (9). The reduction of the flow stress increase this term, reducing again the allowable blank diameter and therefore LDR. If we start the calculation from LDR=1.6 (μ=0.05 and $k_{f,\ micro}$=50 MPa) and change to the macro flow stress k_f=66 MPa, we get an increase from LDR=1.6 to LDR=1.61. This effect is called “global flow behaviour effect”. The remaining effect from LDR=1.61 to LDR=1.8 (which was experimentally determined for macro deep drawing for this material) has to be attributed to the localized failure effect (“local flow behaviour effect”) described above.

6. CONCLUSIONS

- Tribological size effects could be observed in mechanical deep drawing. The friction and the scatter of the punch force increases along with miniaturization.
- The effect of doubling the amount of lubricant can not be detected in micro deep drawing as in macro deep drawing due to the large scatter.
- The limit drawing ratio in micro deep drawing is significantly smaller than in macro deep drawing.
- Size effects on the local and global flow behaviour of work piece material and on the tribology in deep drawing process result in three effects which reduce the limiting drawing ratio in micro deep drawing. The most important one seems to be the local blow behaviour, while the global flow behaviour effect has only a small impact.

ACKNOWLEDGEMENT

The work reported in this paper is funded by the Deutsch Forschungsgemeinschaft (DFG) within the project “Modelling of tribological size-effects in deep drawing” (DFG project no. Vo 530/6-2). The authors would like thank the DFG for their beneficial support.

Moreover the authors would like thank the institute of Metal Forming and Casting (UTG) in Munich in Germany for carrying out the tensile test for the Al99.5 in thicknesses of 0.02 mm up to 0.2 mm.

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GRANIČNA VREDNOST MIKRO DUBOKOG IZVLAČENJA

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REZIME

Mikro duboko izvlačenje postaje sve značajniji proces ne samo u istraživačkim laboratorijama nego i u industrijskoj praksi. Ovaj proces okarakterisan je tz. „size effect"-om (efekat veličine) što pred istraživačima ove problematike postavlja nove izazove. Efekat veličine prouzrokuje povećanje veličine trenja što uslovljava otežano tečenje materijala. Zbog toga je granica deformabilnosti kod mikro dubokog izvlačenja niža od klasičnog dubokog izvlačenja.

Rad se bavi istraživanjima uticaja mikro deformisanja na trenje i tok materijala. Spovedeni su skalirani eksperimenti dubokog izvlačenja sa pet različitih veličina prečnika žiga. Pri tome je analizirani tribološki uticaj „size effect"-a. Ustanovljeno je da koeficijent trenja između materijala i alata raste sa smanjenjem dimenzija procesa.