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Mikropreoblikovanje – Trenutno stanje in prihodnje zahteve

Microforming – Current Status and Future Demands

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Kovinskopreoblikovalno skupnost začenja zelo zanimati mikropreoblikovanje. To lahko razložimo z velikim številom novih uporab in izdelkov, ki so prišli na trg v zadnjih letih. Le-ti vsebujejo vse manjše geometrijske izmere, njihove serije pa so vedno večje. Do sedaj je bila večina teh izdelkov izdelanih s tehnologijami, ki so primerne za maloserijske izdelke. Analiza trga kaže na enakomerno rast potrebe po majhnih izdelkih in zato potrebo po novih tehnologijah, ki so primerne za velikoserijske proizvodnje. Preoblikovanje ustreza tem zahtevam, saj lahko dosega velike natančnosti in ima visoko produktivnost.

Namen tega prispevka je podati pregled trenutnih raziskav mikropreoblikovanja in prikaz zmožnosti te tehnologije. Analiza trenutnega stanja bo dala vpogled na področja, kjer so še vedno luknje v znanju in bi jih bilo treba zapolniti.

(Ključne besede: mikropreoblikovanje, stanja trenutna, zahteve razvoja)

Microforming technology is gaining increasing interest from the metal-forming community. This can be explained by the large number of new applications and products delivered to market in the past, yielding smaller and smaller geometrical dimensions of the final products and thus demanding the smallest specimens to be manufactured in large quantities. Up to now, most of these parts were being manufactured by machining technology, well suited to the production of small series. The analysis of the current market situation shows that the steadily increasing trend towards the smallest products is continuing in the future and thus requires new manufacturing technologies for large-quantity production. Forming technology seems to be well suited due to its high production output and high accuracy.

The aim of this paper is to give an overview of the current research activities related to microforming technology, showing microforming technology's capabilities and problems. The analysis of the current status will give a hint to existing gaps in knowledge and finally describe the future demands.

(Keywords: microforming, current status, future demands)

0 INTRODUCTION

The current production processing for the smallest metallic parts is mainly done using machining or electrochemical technologies, both well suited if small quantity, non-silicon production at a high level of precision level is required. Considering the trend of the past years, leading to smaller and smaller product dimensions and a rapid increase in the production numbers of micro-technical products - from a marked volume of 15 up to an estimated $35 billion in 2002 [1] - the main focus of the manufacturing industry is to be set to other production technologies, like metal forming, which is well-suited to mass production. In order to satisfy these demands, research activities in microforming technologies are being encouraged by a still growing number of research institutes in bulk and sheet/foil metal forming.

1 GENERAL

As mentioned by various authors ([2] and [3]), the forming of specimens with at least two dimensions at the sub-millimetre scale is subject to so-called size effects. They appear when scaling down the process and process dimensions from a conventional length scale to the micro-scale. Although it is required to scale down the process according to similarity theory [4], it is nearly impossible to apply this to all parameters. This can be explained by having a look at two key parameters: the grain size and the surface topography. If an upsetting test is scaled down from the macro-scale (e.g., billet diameter 4 mm, height 6 mm, mean grain size 4 µm, R_a = 1.2 µm) to the micro-scale (e.g., billet diameter 0.5 mm, height 0.75 mm) it is required by similarity theory to reach a mean grain size of 65 nm and a surface roughness of R_a = 0.15 µm. Due to the specimen production process and the material being unchanged, these values are hardly achievable. In addition to the described geometrical sources of the size effects there are, of course, effects due to physical sources [5]. A reduction of the part volume is subject to a reduction of the microstructural features (the number of defects, the number of grains) leading to a change in the failure probability distribution and finally to different plastic behaviour. Other influences are the change in the ratio between the surface and the volume as well as the increasing influence of other forces (Van der Waals and gravity). Depending on the forming process, the fraction of the influence of the parameters on the forming process is different, as will be shown in detail below.

2 BULK METAL FORMING

For investigations on the above-described size effects, various processes (e.g., can backward extrusion, full forward extrusion, double cup extrusion) concerning bulk metal forming have been investigated with respect to forming behaviour, shape building and scaling effects.

2.1 Cold forging

Since the most relevant parameters in forming processes describing the material behaviour are the flow stress and the flow curve, it is necessary to perform scaled standard tests to obtain these parameters that are valid at the micro-scale. Carrying out tensile tests using CuZn15, CuNi18Zn20 [6], copper [7] and aluminium [8] as well as upsetting tests using copper, CuZn15 and CuSn6 ([9] and [10]) two significant effects have been shown: a reduction of the flow stress when increasing the surface-to-volume ratio as well as an increasing process scatter (Fig. 1).

The first approach to describing the decreasing stresses was made by [11], introducing the so-called surface-layer model. Based on the assumption that grains positioned on a free surface have fewer constraints to fulfil than grains within the material, the local forming behaviour of the surface grains must be different. Dislocations induced by a deformation process are able to pile up at grain boundaries, but not at a free surface. Thus, lower hardening occurs in the region of the free surface. Decreasing the specimen size leads to an increasing share of surface grains and thus a lower integral flow curve.

In the case of the full forward extrusion process, scaled from an initial specimen diameter of 4 mm down to 0.5 mm, an increase in the relative punch force was detected, as shown in Fig. 2. A possible explanation for this effect could be the increasing friction with decreasing specimen dimensions. Fur-

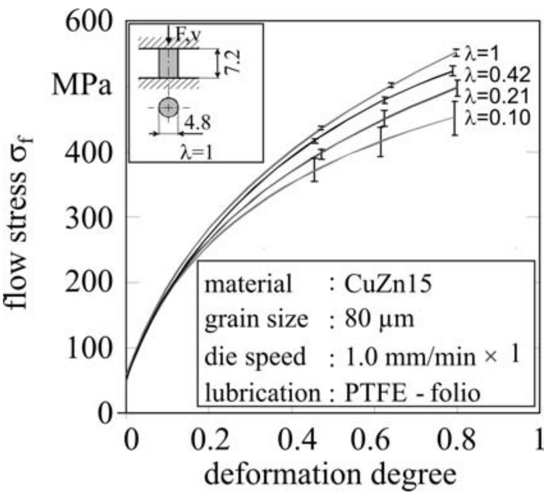

Fig. 1. *Size dependency of the material properties*

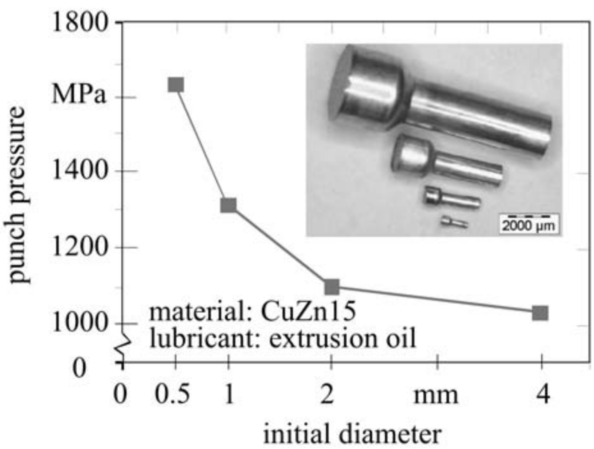

Fig. 2. *Full Forward extrusion*

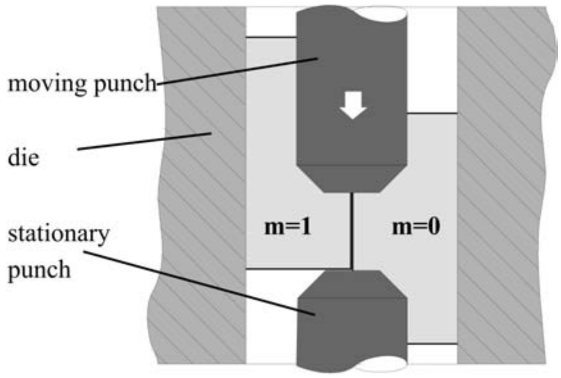

Fig. 3. *Setup of the DCE te*st

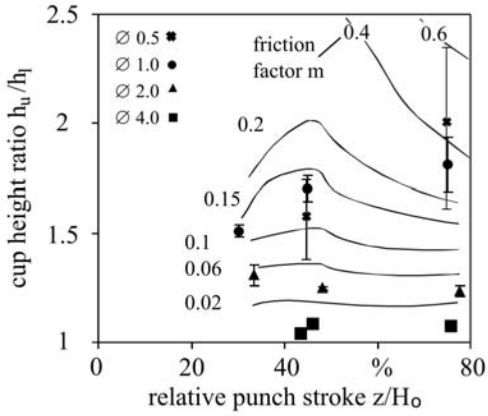

Fig. 4. *Results of the DCE test and the curves of constant friction determined by numerical identification using a FE simulation*

ther tests to study the effects of miniaturization on friction were made by Messner, using the ring compression test [12]. The increase of friction when decreasing the specimen size was analyzed in a more detailed way by [13] using the double cup extrusion (DCE) test, which was first proposed by [14] and applied by [15].

In this test – due to the large plastic deformation being well suited for demonstrating the metal forming processes – a cylindrical billet is positioned between a stationary and a moving punch. Theoretically, in the case of zero friction (m = 0), both cups are supposed to have the same height, but the higher the friction gets, the greater is the height of the upper cup (Fig. 3). Thus, the change in the ratio between the upper and the lower cup is able to characterize the change in the friction conditions. If absolute values of the friction factors are requested, the method of numerical identification can be used (see Fig. 4).

Experimental investigations on frictional size effects have been performed by [13], scaling down specimens that are geometrically similar from a diameter of 4 to 0.5 mm with a ratio of diameter to height $D_0/H_0 = 1$. As can be seen in Fig. 4, the friction increases with decreasing specimen size from a friction factor of about m = 0.02 for the largest specimen up to m = 0.4 for the smallest specimen.

An attempt to describe the frictional behaviour on a topographical level is given by a mechanical-rheological model [13], considering the theory of open and closed lubricant pockets. If a forming load is applied to a specimen surface, the roughness peaks start to deform plastically. From this point on the lubricant is either trapped and pressurized within closed areas, α_{CL}, or squeezed out if a connection to the edge of the surface exists. The forming load can be transmitted into the specimen either by the pressurized lubricant or the flattened asperities.

Due to the scale-invariant production process of a specimen and thus an assumed scale-independent surface topography, the area width where open lubricant pockets appear is constant when scaling down the geometry. Additionally, the area of closed lubricant pockets is reduced and thus the real contact area, α_{RC}, is decreased. This leads to an increase in the friction factor. Further independent investigations have confirmed these results [16].

Based on the mechanical-rheological model, further investigations were performed in order to describe the size-dependent friction factor analytically [17]. Using Wanheim/Bay's [18] friction law and the geometrical boundary conditions, it can be shown that the dependency of the surface topography on the friction factor changes, as it is in good agreement with the experimentally obtained results (see Fig. 5 a-c).

Investigations on micro-extrusion processes with high aspect ratios and large strains have shown a significant dependency of the forming results on the material structure ([2] and [3]). In the case of the backward can extrusion process, the cup geometry was chosen with a cup-wall thickness of about 8 microns. An SEM analysis of the shape building reveals a strong influence of the material structure on the shape building, demonstrated in Fig. 6 by an uneven cup height.

Further investigations using micro-hardness measurements to evaluate the local material flow also confirmed the above-described results. This effect

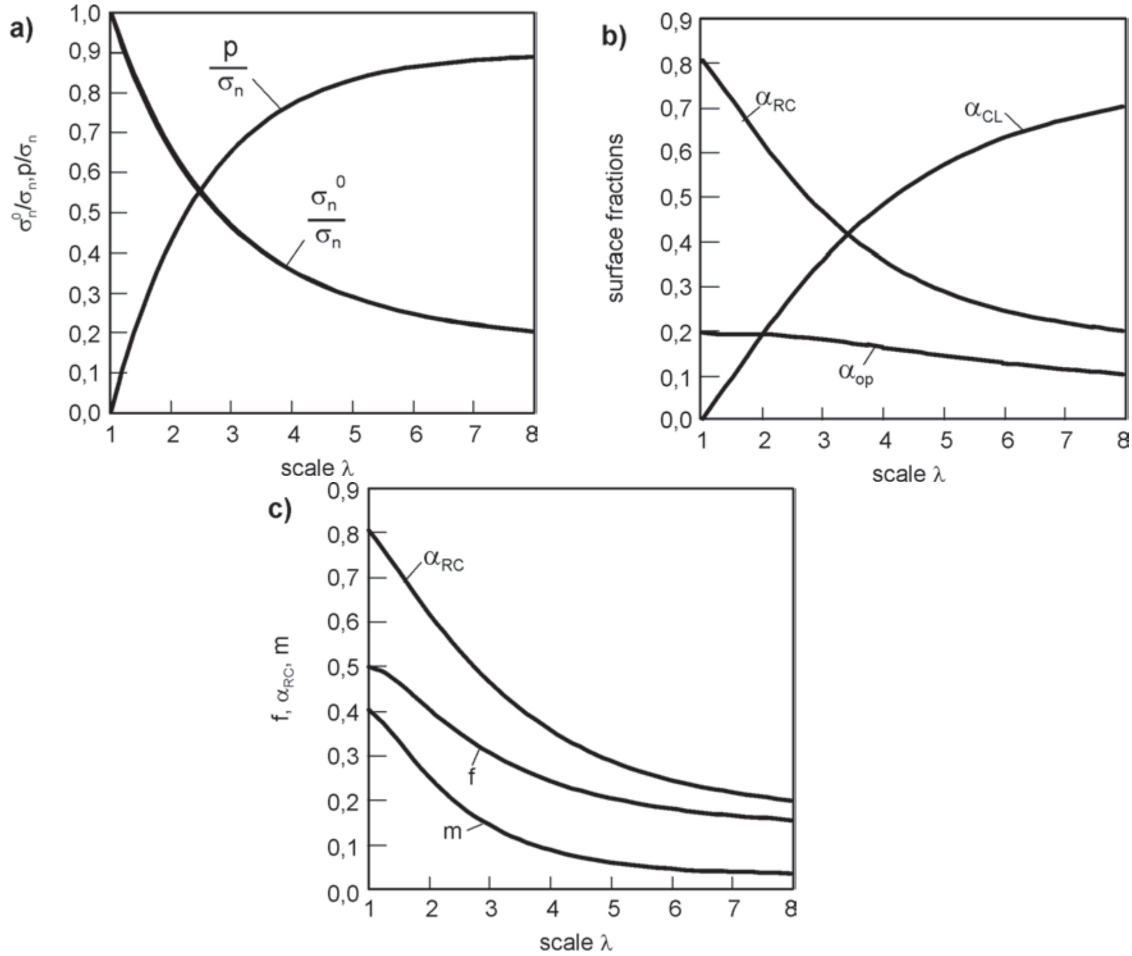

Fig. 5. *Effect of scaling factor λ on p and σ_n^0 normalized to σ_n (a), on α_{RC}, α_{CL} and α_{OP} (b), and on m, f and α_{RC} (c)*

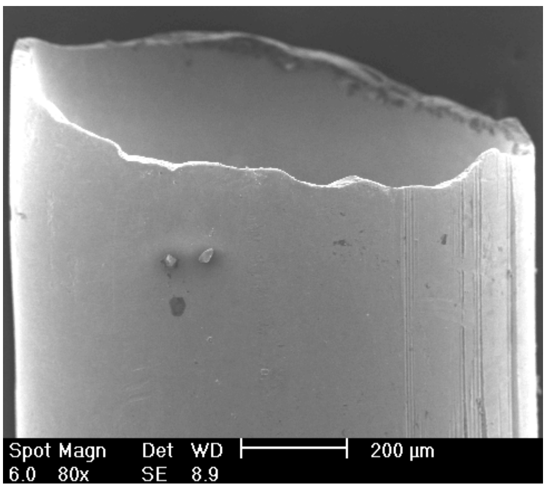

Fig. 6. *Combined full forward cup backward extrusion: effect of specimen size and microstructure on the shape of the extruded parts*

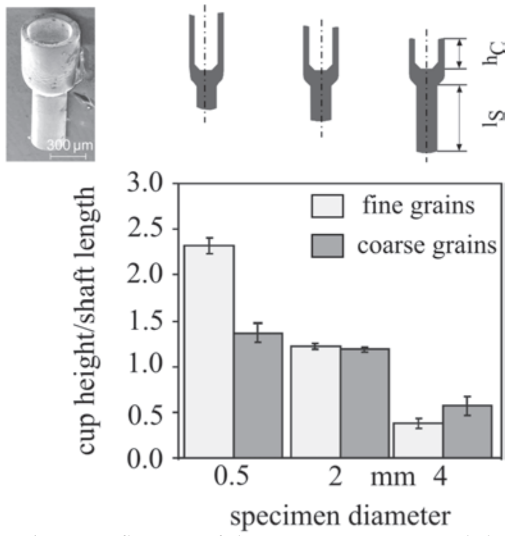

Fig. 7. *Influence of the microstructure and the friction on the shape building using a combined extrusion process*

is less distinct in the case of fine-grained material than in the case of coarse-grained material. In the case of grains being larger than the feature size, they are forced to flow into the smaller features and thus the dependency of the size and orientation causes an uneven cup height.

As expected from the DCE test results, the increase of the friction factor when scaling down leads to an increase of the ratio between the cup height and the shaft length for both cases: coarse-grained and fine-grained material.

The minor increase in the case of coarse grains, shown in Fig. 7, can be explained by the fact that the grain size is in the same range as the feature size. Thus, the material behaviour cannot be considered as polycrystalline; it is easier for the material to flow in the shaft than into the cup.

2.2 Warm forging

An important size-effect at the micro-scale is the large scatter of the process results in the case of cold forging, preventing any application in serial manufacturing processes.

As is known from forming at the conventional length scale, an increase in the forming temperature leads to the activation of additional sliding systems in the material, and thus a decreasing flow stress and a better formability.

To quantify the influence of the elevated temperature on the flow stress at the micro-scale, upsetting tests at different temperatures (20°C, 100°C, 200°C and 300°C) were performed [19]. The material for the tests was CuZn15 and X4CrNi1810 steel. As can be seen in Fig. 8, a significant decrease of the flow curve is achieved, as well as a decrease in the process scatter.

Further investigations on the backward can extrusion process [20] have confirmed these findings. A detailed analysis of material hardening was performed using a micro-hardness measurement system. This enables a strain measurement indirectly on a deformed specimen at high resolution (see Fig. 9). Therefore, the measurement load is set to 20 mN, yielding a minimum distance between two measurement points of 40 microns. The analysis of the local hardening shows clearly that, in contrast to the forming process performed at room temperature, the plasticized area at elevated temperatures is smaller and more concentrated around the punch. Thus, it can be stated that the forming behaviour of the material at elevated temperatures is closer to the one obtained in the macro-case, reducing the characteristics at the micro-scale.

2.3 Coining

Studies concerning the coining of aluminium sheet metal have been performed by Ike and Plancak [21]. Using dies with hole diameters from 0.05 to 1.6 mm, half hard commercially pure aluminium of 2-mm thickness and 30-mm diameter, the coining re-

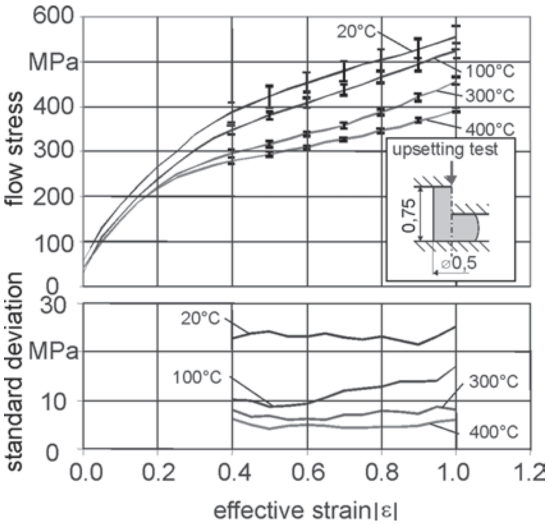

Fig. 8. *Dependency of the flow curve on temperature using CuZn15*

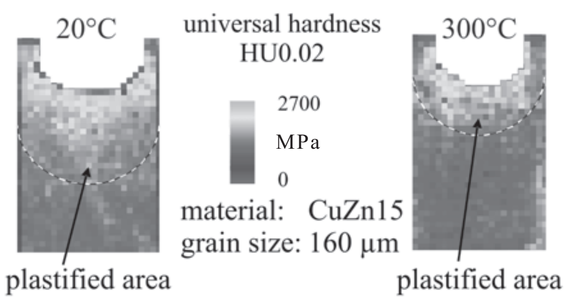

Fig. 9. *Hardness measurement of a formed specimen at elevated temperature*

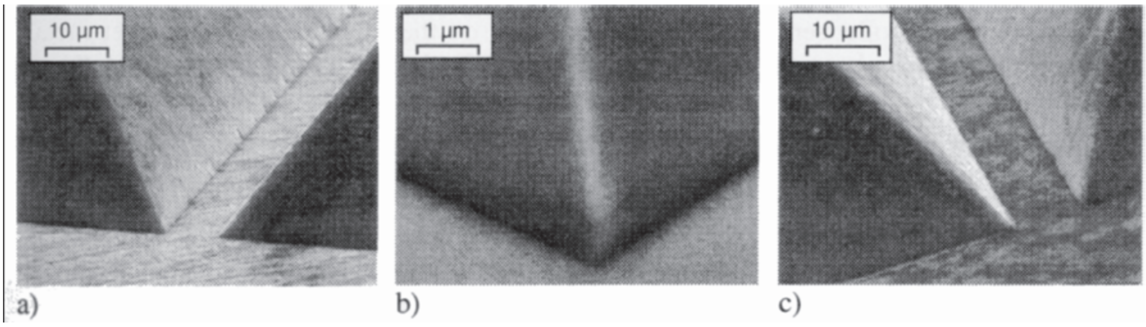

Fig. 10. *Micro-geometry after cold embossing a) aluminium, b) brass, c) stainless steel (IWU)*

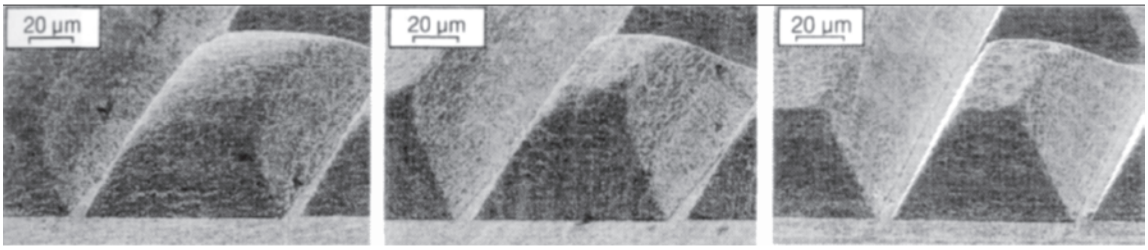

Fig. 11. *Micro-geometry in ZnAl after superplastic coining (IWU)*

sults were evaluated in terms of aspect ratio, the radial position of the hole and the die and the emerging forming load. It was shown that the beginning of plastic flow is independent of the radial position of the hole, but the height of the pins is clearly bound to the position of the holes and its diameter.

At LWP Saarbrücken, Germany [22], the coining of the smallest cavities with a thickness of about 400 microns has been investigated. The results show that in the case of micro-coining the influence of the tool geometry and the tool deflection on the forming results must be considered. This is due to the relatively high nominal stresses (a minimum of three times the flow stress of the coined material) leading to a large influence on the tool system: tool deformation, tool deflection and tool damage.

The aim of the investigations on coining technologies at IWU Chemnitz was to establish this technology for the production of geometrically defined micro-structures for applications in the fields of micro-fluidics, micro-optics and information technology ([23] and [24]). In a first set of experiments the tools were made out of single crystal silicon with an almost smooth surface (Fig. 10). Thus, it was possible to create structures of 100 microns with radii of some 100 nm in aluminium, copper, brass and steel.

The analysis of the coined material shows that the shape of the rim strongly depends on the material. While aluminium shows a maximum bulging of 30% of the coining depth, steel shows a maximum of only 5%. Using a fine-grained ZnAl alloy in a superplastic state at 250°C (Fig. 11), high precision and good surface quality are achieved at low compressive stresses of 25 MPa.

3 SHEET METAL FORMING

Besides bulk metal forming, micro-sheet metal forming plays an increasingly important role, especially in the electronics industry. The smallest lead frames, characterized by lead widths of about 150 microns, or the smallest connectors made by punching, blanking and bending, are some examples.

3.1 Cutting

Basic investigations on the effects of miniaturization on the blanking process were first performed by Kals [6]. It has been shown that the normalized forming force is constant while scaling down the sheet thickness due to a lack of free surface. When the sheet thickness is below a certain value, the forming force and the ultimate shear strength increases. This effect is explained in detail in Section 3.2.

Other investigations have shown that there is a dependency between the tool and process parameters and the accuracy of the produced lead frames. The deflection of the leads in the plane of the sheet increases with the decreasing width of the lead. The deflection is also influenced by the different clearances between the tool and the die in a progressive tool. They also showed that increasing the strip-holder pressure has a positive effect on the accuracy in most cases. Also, the dynamic behaviour of the tool affects the accuracy [25], e.g., increasing the blanking speed results in a reduced accuracy. The performed experiments have additionally shown that increasing the strip-holder force clearly improves the quality of the product. Other investigations on the deflection of a punch during the blanking process [26] have shown an increase when the punch is eccentric, relative to the die.

A particular blanking process, the so-called dam-bar cutting, was investigated in [27] and [28]. This is a mechanical trimming process, removing the dam-bar between the leads after the IC package is encapsulated. Due to the special shape of the specimen, which is rectangular around the IC, investigations have to be performed considering the anisotropic behaviour of the material in the shearing line. Further investigations of different materials have shown that an increase in the angle α reduces the maximum cutting forces, but leads to an increasing burr height.

An important aspect for industrial production is the life of the tool. Therefore, investigations in [28] were performed to show the dependency of the punch forces and thus the tool stresses on the clearance between the punch and the die and the hardness of the used sheet material. While tools made of tungsten carbide (WC) have the longest life time, the tools made of bare HSS show the highest wear. An improvement can be reached by using coatings like TiN or plasma-nitriding. In this case, tools made of steel and WC were compared according to their tool life in an industrial production process for the blades of shavers. While the first only reaches a quantity of 50,000 parts, the latter exceeds 1.15 billion parts. Thus, it is obvious that the use of the more expensive WC as tool material (a factor of 1.8 compared to steel) is more economical than the use of steel.

3.2 Bending

In industrial applications, micro-bending processes are frequently used in the case of spring, clamp or lead frame production. Considering the characteristics of this process, i.e., that the part dimension is close to the sheet thickness, conventional FE simulation programs, which assume plain-strain conditions in the deformed area, are not applicable. In order to overcome this, a first model was developed that makes possible a calculation under plane-stress conditions [29], and there is an improved version that considers the anisotropy of the material [30].

Basic investigations on the relationship between miniaturization and the bending process were first made in [6]. The analysis of the experimental results has shown that the process forces relative to the size decrease with miniaturization in the case of small grains. In the case of large grains (only a few grains over the sheet thickness), the force increases again.

This effect has been confirmed by investigations in [35], performing scaled bending experiments on metallic foils. It was shown that depending on the thickness of the sheet (scaled from 200 microns down to 25 microns) and on the material structure, the bending moment and thus the spring-back angle increases when scaling down. This confirms the previously described theory of strain-gradient plasticity ([31] to [34]).

When scaling down the foil thickness, two contrasting effects appear: the effect of the reduction of the flow stress due to an increasing share of surface grains on the overall volume, and the effect of an increasing flow stress caused by the increasing density of geometrically necessary dislocations. When the foil thickness gets smaller, the latter effect gains a larger influence, resulting in both a higher normalized bending moment (see Fig. 12) and a higher spring-back angle.

3.3 Deep drawing

Deep drawing processes on the conventional length scale are frequently used to produce cups, housings, etc. Basic investigations at the micro-scale were performed by [35]. It was shown that varying the drawing clearance has an influence on both the shape building (see Fig. 13) and the maximum drawing ratio. Independent investigations by Hirt [36] have confirmed these findings.

Further investigations made by Vollertsen [37] evaluated the friction conditions during micro-cup deep drawing. For this approach, the rather complex deep drawing process has been simplified us-

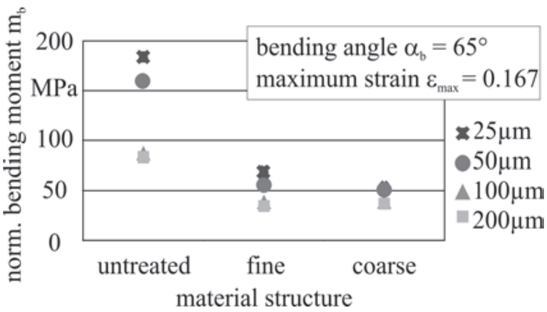

Fig. 12. *The dependence of the bending moment on the sheet thickness and the material structure (LFT)*

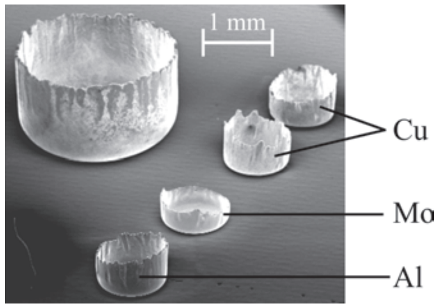

Fig. 13. *Shape of deep drawn cups using different materials (pure copper, molybdenum, aluminium)*

ing a strip deep drawing process with a two-dimensional stress state. The friction coefficients are calculated analytically from the experimental data.

4 SIMULATION

The simulation of the forming processes gains increasing interest even at the micro-scale. Whilst at the conventional length scale, simulation methods are commonly used for the process design. At the micro-scale the simulation programs do not seem to be applicable because of their inability to consider scaling effects.

Sarma et al. [38] carried out FE simulations discretizing the material in different grains, whose forming behaviour depends on the orientation of the crystal lattice associated with each grain and on the critical resolving shear stress parameter of the slip systems. The plastic deformation of the grains is described by modelling grains with different slip plains. Based on Schmid´s law, slip starts when the resulting shear stress reaches a critical value. The material parameters are obtained by fitting the crystal plasticity model to experimentally verified data. Ku et al. [39] did not model the real shape of each grain, but they also discretized the material in grain elements, which are represented by six node elements each consisting of two quadrilaterals. Each quadrilateral is built up of two four-node elements. They also introduced a new so-called grain-boundary element, which is used for the investigation of the sliding and extension between grains. An alternative approach to studying the influence of miniaturization on micro-forming processes by means of a numerical simulation is shown by Engel et al. [40], introducing the so-called surface-layer model. The geometry of the workpiece is divided into two areas: the surface area and the inner area. Within the simulation model two different flow curves are assigned to the two areas. Due to the slight grain-boundary influence on the grains near the surface, the behaviour of these grains resembles that of single crystals, while the behaviour of grains within the material is equal to polycrystals. The transition between the flow stress, $k_{f,I}$, of the inner area and the free surface area, $k_{f,FS}$, is described in a discontinuous way. This approach explains the reduction of the integral flow stress with the decreasing size of the workpieces, but it is not able to show the influence of the grain structure on the scatter of the forming factors. Another disadvantage is the result of the unsteadiness of the flow stress at the transition from the inner material area to the surface area [41]. Based on the above-described surface-layer model, another approach has been realized by considering the material structure in a simulation programme [42] (see Fig. 14). Several techniques for the computational generation of grain structures have been developed. Among these, Monte-Carlo-Potts models, vertex tracking, front tracking, Voroni tessellation, phase field approaches and cellular automata are examples for different grain-generation technologies. Cellular automata are algorithms to describe the evolution of complex systems by using transformation rules. They are specified by a set of deterministic or stochastic transformation rules that are applied to the sites of a lattice. The lattice is typically regular and defined by a number of points that carry the actual values of the state variables, e.g., particle density. Probabilistic cellular automata also allow a statistical description of grain growth [43]. It has been shown that the so-called mesoscopic model is able to consider scaling effects like the decrease of the flow stress when scaling down the process as well as the increase of the process scatter.

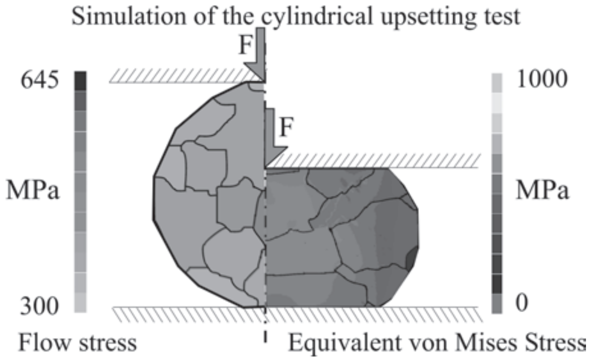

Fig. 14. *Mesoscopic model*

5 CONCLUSIONS

As can be seen from the large amount of research activities in the field of microforming, some aspects are already identified and described, but several problems are still unsolved. Thus, only a few applications in this relatively wide field are already industrially applicable (especially in the field of microelectronics), other applications are close to a breakthrough. In most research areas great effort has been made to identify the size effects, now these effects must be described and solutions must be proposed to solve the problems that occur. This can be done purely academically, but considering the great advantage of the forming process for serial manufacturing, it will also be reasonable to start future research activities together with industry, not only to enhance process knowledge but also its usability and stability.

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