Spring-back behaviour of thin metal foils in free bending processes

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Abstract

Metal foils attract a large field of applications, e.g. in micro-technology they are being used for sensors, actors, micro-electro-mechanical systems and in medical devices. Conventional sheet metal forming processes are in principle applicable for metal foil forming. Reducing the sheet thickness to the order of micrometers, however, causes various scaling effects. Therefore, the know-how of conventional sheet metal forming cannot be transferred directly to metal foil forming. A known phenomenon during foil forming is the reduction of strength of the material with decreasing thickness due to the increasing share of surface grains with fewer constraints to plastic flow on the overall volume. The opposed phenomenon is the increase of material strength regarding foils with mean grain sizes in the range of the foil thickness or even higher.

In the present paper basic research via scaled free bending tests is performed to investigate size effects in order to provide basic knowledge for the design of the process and of the components, respectively. An important factor in production accuracy of bending processes is the spring-back. In the current research spring-back of aluminium foils (Al 99.5) in dependence of the foil thickness is investigated with foil thicknesses ranging from 25 to 200 microns. Variation of the mean grain size/foil thickness ratio is achieved by different heat treatments. The experimental results are being compared with FE-simulations.

Keywords: micro-forming, spring-back, metal foils

1. Introduction

Many technical fields, e.g. electronic industry, are faced in several areas with progressive miniaturisation. Resulting from this trend the demand for accurate forming processes of thin metal foils, which are used for the production of micro parts like sensors, actors or other micro-electro-mechanical systems is growing [1]. Typical processes in micro sheet metal working are blanking and bending [2].

Reducing part dimensions to micro scale, however, leads to so called size effects which are subject matter for several investigations [2]. Due to the size effects existing know-how of conventional forming processes cannot be applied directly to micro-forming processes. The decisive parameter for the occurrence of size effects in micro sheet metal forming is the ratio of mean grain size $L_0$ to foil thickness $t_0$. In case of micro bending processes, there are two main contrary size effects. With decreasing foil thickness the material strength is decreasing due to the increasing share of surface grains with fewer constraints and thus different forming behaviour compared to grains within the material [3]. This effect has been verified by many independent investigations [2,4,5], finally leading to the development of the surface layer model [6] which describes this size effect sufficiently for most applications. The contrary effect of an increasing material strength with decreasing foil thickness can be observed for processes exhibiting large strain gradients, e.g. bending processes. if the foil thickness is in the range of the grain size, i.e. the ratio $L_0/t_0$ is in the range of one [7]. An explanation of this effect is possible using dislocation theory. According to Ashby [3] dislocations in a non homogeneous material can be subdivided in statistically stored and geometrically necessary dislocations. As a characteristic of a material, the density of statistically stored dislocations $\rho_s$ depends on the crystallographic microstructure, shear modulus and the stacking fault energy. In contrary the geometrically necessary dislocation density $\rho_0$ is in first approximation independent of the material and solely depends on the geometric relations and size of the material grains and phases. In bending processes, $\rho_0$ is related to the applied curvature by equation 1

$$\rho_0 = C_b/b$$

where $C_b$ is the beam curvature and $b$ the Burgers vector. While the contribution of $\rho_0$ to the materials shear strength is negligible for small curvatures, i.e. large bending radii, it becomes more significant for large curvatures, i.e. small bending radii. A decrease of the bending process dimensions according to the theory of similarity is not affecting the strain but increases the curvature and therefore the applied strain gradient. Thus, the influence of $\rho_0$ on the mechanical behaviour of thin foils in bending is increasing with decreasing foil thickness.

The latter size effect has been verified with only few experiments which not only include bending processes but also torsion processes and hardness measurements [8]. Therefore further investigations regarding this issue are necessary. An approach for a theoretical description of the influence of $\rho_0$ on the plastic behaviour of thin foils is based on the so called strain gradient plasticity [8,9,10] which considers strains as well as their gradients.

Based on this theory, in [11] a plasticity length scale parameter is suggested for an advanced description of the bending of nickel foils with thicknesses of 12.5 µm, 25 µm and 50 µm using a microbend test method. The same method is used by [12] for LIGA nickel foils (thickness 25 µm to 175 µm).
Other investigations of free bending processes with significant influence of strain gradients focused on the required bending forces \cite{4,7} or strain distribution in the forming area \cite{13}.

Established methods to investigate size effects are scaled experiments, taking into account the theory of similarity. For this approach all parameters of the experiments (foil thickness, bending radii, punch velocity, etc.) are adapted by a scaling factor \( \lambda \). In this paper the results of scaled free bending experiments of Al 99.5 foils with thicknesses ranging from 25 \( \mu \text{m} \) to 200 \( \mu \text{m} \), i.e. scaling factor ranging from \( \lambda = 0.125 \) to \( \lambda = 1 \) are discussed.

The parameter of interest is the spring-back which gives an indirect measure of the applied bending moment and is furthermore a decisive value for product accuracy. The \( L_G/t_0 \) ratio is varied applying different heat treatments to the investigated foils and thus, the influence of the contrary size effects on the bending process can be examined in dependence on this ratio. The experimental results are compared with results from FE-simulations.

2. Experimental Procedure

2.1. Characterisation of the material

The material used for the experiments was pure aluminium (Al 99.5) with foil thicknesses ranging from 25 to 200 microns. The material was characterised by metallographic means and tensile tests.

To achieve a variation in mean grain size \( L_G \) and thus a variation of the \( L_G/t_0 \) ratio different heat treatments were applied to the material. Table 1 summarises the microstructural parameters of the examined material.

<table>
<thead>
<tr>
<th>Foil thickness</th>
<th>( L_G ) (fine)</th>
<th>( L_G ) (coarse)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 ( \mu \text{m} )</td>
<td>21 ( \mu \text{m} )</td>
<td>38 ( \mu \text{m} )</td>
</tr>
<tr>
<td>100 ( \mu \text{m} )</td>
<td>19 ( \mu \text{m} )</td>
<td>52 ( \mu \text{m} )</td>
</tr>
<tr>
<td>50 ( \mu \text{m} )</td>
<td>22 ( \mu \text{m} )</td>
<td>36 ( \mu \text{m} )</td>
</tr>
<tr>
<td>25 ( \mu \text{m} )</td>
<td>14 ( \mu \text{m} )</td>
<td>36 ( \mu \text{m} )</td>
</tr>
</tbody>
</table>

Since the grain size in direction of the foil thickness is restricted, the grain size values were determined along the foil plane. In case of thin foils with coarse grain structure (\( L_G/t_0 \) ratio < 1) only few grains exist in thickness direction with a minimum of one grain as it is illustrated in Fig. 1.

![Fig. 1: Microstructure of Al 99.5 foil, \( t_0 = 25 \mu \text{m} \) with coarse grain structure](image1)

The mechanical characterisation of the foils was achieved by tensile tests including both states of grain structure (fine, coarse). For foils with fine grain structure only a slight size effect can be observed, whereas the flow stress of foils with coarse grain structure is decreasing significantly with the mean grain size (see Fig. 2).

![Fig. 2: Flow stress of Al 99.5 foils at true strain \( \varphi = 0.01 \) with coarse and fine grain structure](image2)

This effect can be put down to the increasing share of surface grains with increasing mean grain size. Surface grains exhibit lower yield strength due to fewer constraints with the surrounding material.

For both annealed microstructures the maximum strain to fracture \( \varphi_{fr} \) decreases with decreasing foil thickness, while \( \varphi_{fr} \) is higher for fine grain foils as shown in Fig. 3.

![Fig. 3: Strain to fracture in dependence of foil thickness for coarse and fine grain structure](image3)

One explanation for these findings is the increasing surface/volume ratio with decreasing foil thickness. Hence the influence of surface defects on the plastic behaviour is growing and the critical defect size leading to fracture is decreasing with the cross section area and thus with foil thickness.

2.2. Bending Tool

A bending tool for the realisation of scaled free bending experiments has been developed. The principle set up is illustrated in Fig. 4.

The tool mainly consists of an upper and a lower part and is installed in a universal testing machine UTS 5K. The punch is guided by a 4 rod guiding system

![Fig. 4: Principle set up of the bending tool used for the free bending experiments](image4)
which ensures an in-parallel relative movement of die and punch. Different stroke lengths are defined by adequate mechanical stops. Positioning of the punch and die is achieved by a guiding assembly and locating pins. The die width is adapted using an adjusting screw and metered by a dial gauge.

2.3. Bending experiments

Free bending experiments were conducted using the bending tool as described above. The process parameters punch radius $r_p$, die radius $r_d$, die opening width $W$ and punch velocity $v_p$ for the experiments were chosen according to the theory of similarity (Table 2). Due to the scaling, the maximum strain $\varepsilon_{max}$ (eq. 2) on the upper surface of the bending area remains constant ($\varepsilon_{max} \approx 0.167$) for all foil thicknesses.

$$\varepsilon_{max} = \left(\frac{\lambda \cdot t_0}{2 \cdot \lambda \cdot r_m}\right)$$

where $r_m$ is the bending radius of the neutral layer.

Table 2: Process parameters of the free bending experiments

<table>
<thead>
<tr>
<th>Scaling factor $\lambda$</th>
<th>$r_p$; $r_d$</th>
<th>$W$</th>
<th>$v_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>500 µm; 240 µm</td>
<td>4 mm/min</td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>250 µm; 120 µm</td>
<td>2 mm/min</td>
<td></td>
</tr>
<tr>
<td>0.25</td>
<td>125 µm; 60 µm</td>
<td>1 mm/min</td>
<td></td>
</tr>
<tr>
<td>0.125</td>
<td>62.5 µm; 30 µm</td>
<td>0.5 mm/min</td>
<td></td>
</tr>
</tbody>
</table>

The preparation of the bending specimens was done by laser cutting with a Nd:YAG laser. One strip contains six bending samples and is positioned in the bending tool by fixing pins to ensure constant process conditions. The geometry of the specimens is depicted in Fig. 5.

The bending process was recorded via CCD-camera. From the recorded pictures both bending and spring-back angle were determined automatically by means of image processing. In Fig. 6, a recorded and a processed CCD image of an exemplary bending experiment are illustrated.

In absence of any size effect the spring-back mainly depends on the process parameters and the material properties. Due to the small die opening width, a constant bending radius $r_b$ is assumed for all bending angles. With this assumption, the spring-back angle $\alpha_s$ depends linearly on the bending angle $\alpha_b$ since the spring-back ratio $R_s$ (eq. 3) remains constant for constant bending radii.

$$R_s = \frac{r_b}{r_s} = \frac{\alpha_b - \alpha_s}{\alpha_b} = 1 - \frac{\alpha_s}{\alpha_b} = \text{const.}$$

where $r_s$ is the radius of the neutral layer after spring-back.

As it can be seen (Fig. 7) the observed spring-back angle of the annealed foils is consistent with the above described theory, and thus verifies the experimental procedure. Foils of 25 µm in thickness and coarse grain structure show no clear linear dependence on the bending angle, which possibly is due to the small $L_G/t_0$ ratio and the increasing influence of single grains in the bending area.

The influence of the foil thickness on the spring-back is shown in Fig. 8 where the spring-back angle $\alpha_s$ is plotted against the scaling factor $\lambda$ for a bending angle of 65°. The spring-back angle of the foils is significantly increasing with decreasing foil thickness for fine and coarse grain structure.

The influence of the mean grain size on the spring-back behaviour becomes clear by comparing the increase of spring-back of foils with fine and coarse microstructure (Fig. 8). While there is a similar spring-back angle for larger foil thicknesses (100 µm < $t_0$ < 200 µm), the spring-back angle of thinner foils (25 µm < $t_0$ < 50 µm) differs depending on the mean grain size. Foils with fine microstructure show a stronger increase of spring-back angle with decreasing foil thickness than foils with coarse microstructure. Since, for the same foil thickness, the same strain gradient is present, this difference is due to the influence of surface grains. The share of surface grains on the overall volume is smaller for fine
microstructures and thus the resistance against plastic deformation is higher. Therefore a smaller plastic zone and larger elastic zone will arise in the bending zone of foils with fine microstructure compared to those with coarse microstructure. Hence, the spring-back angle as a result of elastic recovery becomes larger for fine microstructures.

2.4. Comparison of experimental results with FE-simulations

During free bending of thin foils a combined influence of the share of surface grains and of strain gradients on the bending process is present. To estimate the contribution of each effect on the detected integral size effect, FE-simulations of the free bending process were conducted, taking into account the specific flow curves for each foil thickness and microstructure, determined by the tensile tests (see chapter 2.1).

FE-simulations were done using the software MSC/Superform 2004. The model consists of 1916 square elements with 10 elements over thickness to ensure an appropriate simulation of the elastic behaviour. Experimental results are compared with results of FE-simulation. As it can be seen in Fig. 8 the simulation results are in acceptable agreement with the experimentally determined spring-back for the macro case of $\lambda = 1$ and thus verifying the model. For both annealed structures the difference between simulated and experimental results is increasing with decreasing scaling factor (see Fig. 8). Since the integral size dependent flow curves were integrated in the simulation, the simulative spring-back is decreasing with decreasing foil thickness, whereas the experimental spring-back is increasing with decreasing foil thickness. The experimental results are therefore influenced by a contrary size effect controlled by the increasing strain gradient with decreasing foil thickness.

3. Conclusions and outlook

The spring-back of thin Al 99.5 foils is increasing with decreasing foil thickness. It has been verified that the spring-back behaviour is influenced by two contrary effects. The contribution of these effects on the spring-back behaviour is dependent on the material grain size.

Due to the increasing share of surface grains with lower yield strength spring-back is reduced with increasing mean grain size. This size effect is superposed by the contrary effect of material strengthening due to an increasing density of geometrically necessary dislocations caused by increasing strain gradients with decreasing foil thickness.

Further experiments with different maximum strains are needed, to enable the determination of a length scale parameter describing the contribution of the strain gradient on material strengthening. Including this relation in the FE-model would lead to an improved predictability of micro sheet forming processes exhibiting large strain gradients.

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References


Fig. 8: Comparison of experimental and simulative spring-back of annealed foils: a) coarse microstructure; b) fine microstructure