Process parameter interaction in microforming

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ABSTRACT: Microforming processes, size effects and the influence of distinctive parameters on the forming process are been investigated for a long time. This paper presents some results of parameter interactions influencing the microforming process. The effects and interactions of five selected parameters are investigated for a full backward extrusion of small pins by means of a full factorial experimental design. The temperature-pin diameter interaction is used to give an example of an obvious and significant parameter interaction.

Key words: Microforming, size effects, parameter interaction, Cu-ETP

1 INTRODUCTION

During the last decade, numerous large and small scale projects have been established worldwide, in order to investigate micro-manufacturing processes. The goal of some of these projects was to understand the fundamentals of forming processes at micro-scale, as simple miniaturisation of reliable and well known forming processes from conventional scale to micro scale does not yield the expected results. So called size effects appear when the whole process is scaled according to the theorem of similarity [1], impeding the transfer of existing know how from macro to micro scale. The impact of these size effects on the process results like scatter of process characteristics or shape evolution are one of the main reasons preventing microforming technology from being widely used at industrial large scale manufacturing of smallest metallic components.

A large number of experimental investigations on various deformation processes have been done to understand and to describe the impact of different parameters on the forming process, the deformation behaviour and the forming results at microscale [2, 3]. The knowledge gained by these investigations has been expressed by various analytical and numerical models. For example the surface layer model [4] and the mesoscopic model [5], describing the decrease of the integral yield strength due to the increasing share of surface grains in case of open die processes at microscale, or the mechanical rheological model [6]. This model describes the increase of the friction due to the significantly changing of the surface to volume ratio when scaling down geometrical dimensions. Other investigations had their focus on the reduction of the microforming drawbacks, like the increased scatter or the irregular shape evolution. One of these approaches to reduce the scatter is done by forming at elevated temperature [7]. All the investigations have proven that forming processes and forming behaviour sensitive to specific process parameters are. While in most of the previous work, the process influence of only particular parameters was investigated, this paper is aiming at the investigation of process parameters' interaction. It is known, that specific parameters possess a certain influence on the forming process, but it can be assumed that the magnitude of these effects is strongly depending on the settings of other parameters. As microforming processes are known to be very sensitive to changes of relevant process parameters, it is necessary to understand and to control all these parameters as well as their interaction within tight tolerances. Thus it will be possible to utilise the potential of microforming processes for the production of small, but complex micro components. In order to investigate the parameter interaction a full factorial experimental process design with five parameters has been established. The five chosen parameters, depicted in figure 1, are known to have a significant influence on microforming processes.

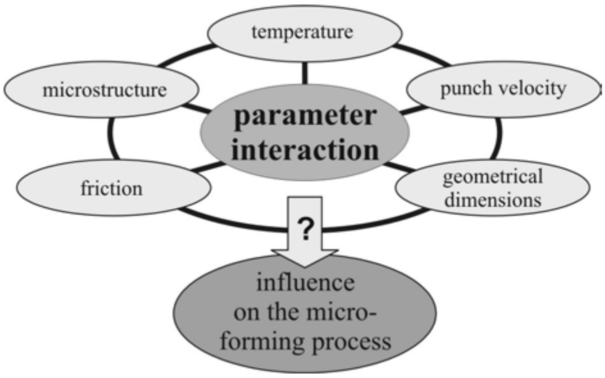

Fig. 1. Relevant parameters for the investigation of parameter interaction

2 EXPERIMENTAL SETUP

The investigation of the parameter interaction is done by using a full backward extrusion process, forming an axially symmetric pin. This process has been chosen due to its high sensitivity on the five selected parameters with their upper and the lower limits are listed in table 1.

Table 1. Parameter limits

Parameter		Lower limit	Upper limit
Temperature	T	20°C	200°C
Grain size	l_g	Fine grained (28 µm)	Coarse grained (80 µm)
Punch velocity	v	3 mm/min	30 mm/min
Lubrication	lub	none	Drawing oil
Pin diameter	d_p	0.5 mm	2.0 mm

The material used for the investigation is high conductivity copper (Cu-ETP). All the specimens feature a diameter of 12 mm, a height of 10 mm and are manufactured by turning. In order to obtain an isotropic grain structure, minimizing any effects caused by production processes of the rod, a heat treatment above recrystallisation temperature is done prior to the specimen manufacturing. The average grain size l_g for fine and coarse grained material is defined by the applied heat treatment.

The tools used in these investigations consist of an upper punch and a lower die. In order to extrude pins at different sizes, punches for different pin diameters are manufactured. The pin cavity and the corresponding corner radius are scaled with the factor λ, as sketched in figure 2. Three different punches are used with the scaling factor $\lambda = 0.5$, 1 and 2, corresponding to a pin diameter of $d_p = 0.5$ mm, 1 mm and 2 mm.

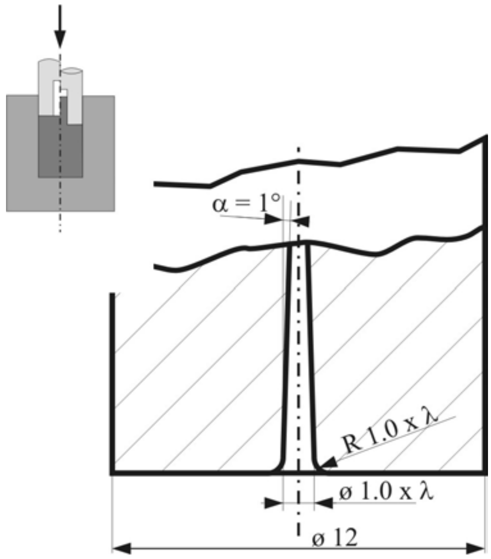

Fig. 2. Geometrical dimensions of the punch

The characteristic process result of the extrusion process regarding the different parameter settings is the pin's obtainable aspect ratio, calculated as ratio of pin height and the pin diameter.

By using FE-Simulation for both tool design and process simulation it can be shown, that forces above 50 kN are necessary to extrude even small pins. For the extrusion of pins with high aspect ratio, higher forces in the range of 200 kN are required. Due to the high forces and the related high stresses a presstressed die is necessary as well as a rigid upper and lower tool holder. The precise alignment of die and punch is assured by a tightly tolerated guiding system. In order to perform the experiments at a temperature range between 20°C and 200°C, special heating sleeves are surrounding the punch-holder as well as the die-holder. Via heat conduction the specimen, enclosed by the die, are heated by the heating sleeve. By controlling the temperature, a constant forming temperature during the deformation process can be realised.

The experiments are performed on a Schenk Trebel universal testing machine. All the tests have been run up to a maximum force of 200 kN.

Additionally, cross-sections along the pin axis are metallographically prepared in order to investigate the local deformation behaviour by analysing micro-hardness measurements.

3 RESULTS

The screening of the five factors at two levels with more than 32 different parameter combinations (supplementary centre points have been added) has shown that most of the parameters have a significant influence on the forming behaviour and therefore affect the obtainable aspect ratio. In order to understand the parameters' interactions, the particular main effects have to be investigated first. A particular main effect is the aspect ratio difference when changing only one parameter from its lower limit to the upper limit, averaged for all other parameter combinations. The calculated average effects of the five parameters, extracted from more than 200 experiments, are shown in figure 3. The error bars indicate the confidence interval based on a 95% confidence level.

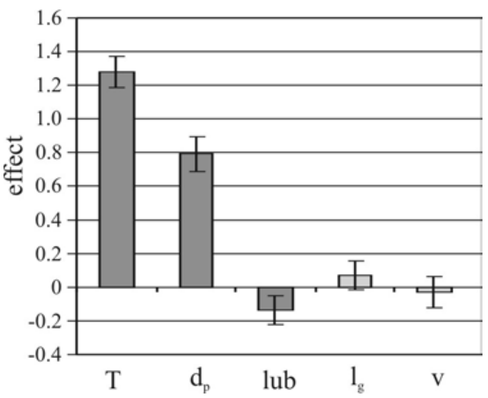

Fig. 3. Parameter effects

The parameter with the largest influence is identified to be the temperature *T*, followed by the pin diameter d_p and the lubrication *lub*. These three parameters can be identified to have a significant impact on the aspect ratio. An average aspect ratio increase of 1.28 can be achieved by increasing the forming temperature from 20°C to 200°C, regardless of the other parameter settings. When changing the pin diameter from 0.5 mm to 2 mm, an average increase of the aspect ratio of 0.8 can be observed. Comparing the experimental results for all parameter combinations (lubricated and none lubricated), nearly all experiments show, that a higher aspect ratio can be reached for non lubricated specimens. In only two cases with a forming temperature *T* of 200°C, a slow punch velocity *v* of 3 mm/min and a d_p of 1.0 mm and 2.0 mm, the lubrication yields a better formability. The main effects of the grain size l_g and the velocity *v* are rather small. Since the confidence interval is larger the calculated effect, it is possible that the observed effect is caused by randomness, thus the influence of both parameters can not be identified to be significant.

The following section describes the impact of parameter interactions on the aspect ratio in contrary to the main effects described above. For the analysis of the temperature-pin diameter ($T*d_p$) interaction, the aspect ratio alteration caused by a temperature change will be compared for a 2 mm and a 0.5 mm pin diameter. Pictures of the extruded pins at both temperature levels can be seen for the different pin diameters in figure 4 and figure 5, respectively. In this example all other parameters are set constant to: grain size fine, velocity 3 mm/min, lubrication none.

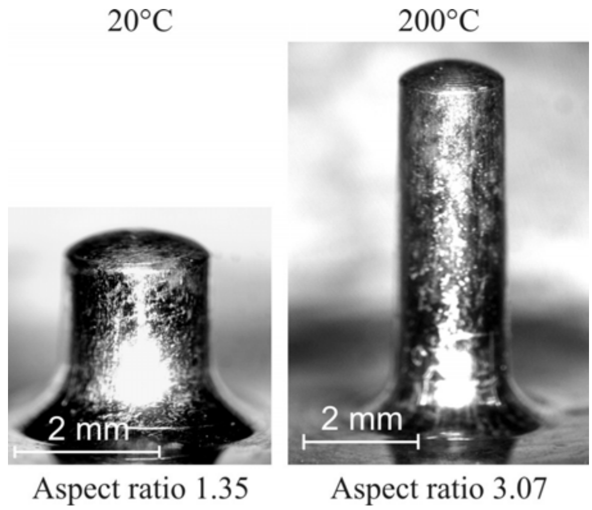

Fig. 4. Temperature effect on the aspect ratio pin diameter 2.0 mm

In the first case, the aspect ratio can be increased by 1.72 (127%) from 1.35 to 3.07, by changing the temperature level. A similar but less distinctive behaviour can be observed for the 0.5 mm pin diameter (figure 5). In this case the aspect ratio increase is 0.77 (90%) from 0.86 to 1.63.

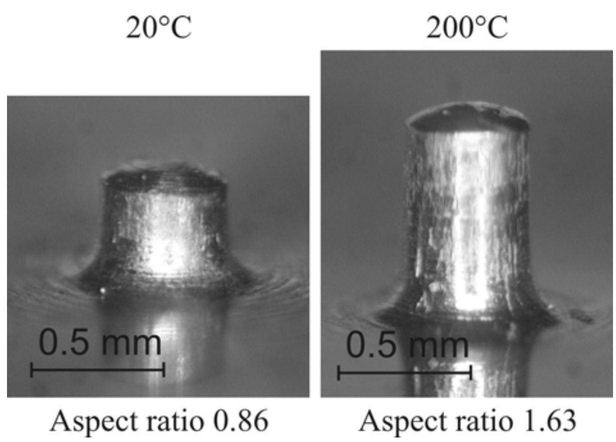

Fig. 5. Temperature effect on the aspect ratio pin diameter 0.5 mm

It should be noted that the geometrical effect is also influenced by the restriction with respect to the layout of the experiment being not scaled perfectly according to the geometrical similarity, since the outer dimension in combination with the maximum load is kept constant. This restriction is directly influencing the nominal upsetting stress, controlling the material flow as well. However, it can be shown that the effect of this restriction is less than 3% which for the first approach and in view of the observed effects can be neglected.

When comparing the aspect ratio increase of 1.72 and 0.77 due to the temperature effects for the 2.0 mm and the 0.5 mm pin diameter, respectively, it is obvious that the magnitude of the increase is strongly depending on the dimension of the pin diameter. The calculated value of the $T*d_p$ interaction for this parameter setting is 0.48. Comparing this result with the calculated average interactions shown in figure 6, this value for one parameter combination fits well the overall $T*d_p$ interaction of all other parameter settings.

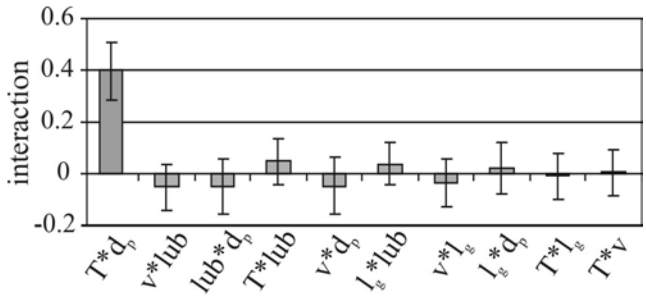

Fig. 6. Average parameter interaction

From the analysis of all experiments, shown in figure 6, only the $T* d_p$ interaction is significant at a 95% confidence level. But a closer look at selected results at several parameter combinations indicates that also other interactions take place. It will be expected, that more and smaller interactions will be observed and identified to be significant with additional experiments and an adapted experimental design.

4 CONCLUSION

The screening of the five parameters with a full factorial experimental design and more than 200 experiments has shown that significant effects and interactions can be identified for forming processes at microscale. It also shows that some of the parameter interactions have a clear impact on the process result while other parameter interactions are rather small and cannot be identified to be significant so far as all experiments are superimposed by random process scatter. Additional experiments and an adapted experimental design are expected to enhance the provided information on the process and its scatter and thus be able to identify in more detail parameter interactions.

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