Lecture Notes in Production Engineering

Frank Vollertsen *Editor*

Micro Metal Forming

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Preface

Currently, our life is characterized by a continuous densification in all aspects and parts. Communication is faster thanks to smartphones, enabling one-to-one video, and audio contact nearly at any time and location. Smartphones have a large number of functions, which were realized before by nearly a dozen of aggregates. Comfort and safety in cars is increased by a steadily growing number of safety and assist systems, controlling not only the status of the car functions itself, but also the agility of the driver and the actions of the traffic around the car. Also, health care components comprise numerous functions in aggregates of reduced size. All those developments are the drivers for miniaturization of parts and components which have to be produced in large lot sizes at low costs. As metals are still excellent multi-functional materials, the methods of metal forming could be a means of covering these demands, if those processes could be used for the production of miniature components.

A first hot spot of micro metal forming in Germany was developed by Prof. Engel and Geiger, starting in the 1990s in Erlangen. Discussion of the scientific advances, achieved also in other countries like Japan and USA was held (not limited to but also) in The International Academy for Production Engineering (CIRP), documenting the milestones in numerous papers and two keynote papers. These keynote papers ('Microforming', issued in 2001, and 'Size effects in manufacturing of metallic components', issued in 2009) are key documents on the development of micro metal forming. The relevance of size effects is due to the fact that those effects are the reason why knowledge from (macro) metal forming cannot be transferred easily to the micro range. The effects have been the topic of a priority program funded by the Deutsche Forschungsgemeinschaft (DFG) in the period from 2002 to 2008. In 2007, a Collaborative Research Center (CRC, SFB 747) was started in Bremen, funded by the DFG and the University Bremen. Within this CRC are about 50 scientists' work on topics relevant for the further development of micro metal forming. Taking advantage of the structure of a University, lectures on micro metal forming are introduced and held continuously by the CRC-scientists. The knowledge gathered and produced in the CRC is condensed in the hand book. It is compiled to help those people who start to work in this special field of micro metal forming. It is not only for students, doing their Bachelor or Master thesis, but also for engineers working in research and development in institutes and industry. Basic knowledge of physics, mathematics, and the principles of metal forming are required to use this book.

The aim of this book is to present the most important basic knowledge, the current state-of-the-art, and research results useful for future application of micro metal forming. Hence, the book is composed from three blocks, each comprising some chapters:

The first block (Chaps. 1–3) describes the basics in metal forming like tribology, formability, and mechanical strength. A special emphasis is laid on the questions which arise when reducing the size to the micro range. Therefore, size effects are also described which should help to understand the principle differences in micro forming besides the small size and weight of the workpieces.

Information on processes of bulk and sheet forming is given in the second block (Chaps. 4–6). Besides the effects in micro metal forming using the common processes, special processes which make use of size effects are explained in Chap. 6. The processes are only feasible in micro processing and demonstrate the positive nature of size effects. The facts explained in the first block are helpful to understand the nature and limits of those methods.

Tools in the broader sense, which are used for micro metal forming, are addressed in the third block. Not only the forming tools, e.g., the components which transfer forces on the workpiece during the forming process are meant, but also means for their production and other aggregates like forming machines, methods for quality assurance, and simulation tools. These topics are described in Chaps. 7–10.

All the authors of the 10 chapters and sections are working in the relevant fields of the CRC. They are directors or staff members of the following institutes, listed in alphabetical order together with the most important research areas covered within the CRC. The names of the directors are given in brackets:

BIAS—Bremer Institut für angewandte Strahltechnik: Laser material processing, sheet and bulk metal micro forming (Prof. Dr.-Ing. Frank Vollertsen); optical metrology (Prof. Dr. rer. nat. Ralf Bergmann)

BIBA—Bremer Institut für Produktion und Logistik: Logistics and simultaneous engineering (Prof. Dr.-Ing. Bernd Scholz-Reiter)

BIMAQ—Bremer Institut für Messtechnik, Automatisierung Qualitätswissenschaft: Process control including metrology, quality assurance (Prof. Dr.-Ing. Gert Goch)

bime—Bremer Institut für Strukturmechanik und Produktionsanlagen: Bulk metal forming including machine development (Prof. Dr.-Ing. Bernd Kuhfuß; process chain layout and automatization (Prof. Dr.-Ing. Kirsten Tracht)

IfS—Institut für Statistik: Monte Carlo-simulation and statistics (Prof. Dr. Mag. rer. nat. Werner Brannath)

IWT—Stiftung Institut für Werkstofftechnik: Physical vapour deposition, heat treatment, and mechanical testing (Prof. Dr.-Ing. Hans-Werner Zoch)

LFM—Laboratory for Precision Machining: Cutting, machining, and polishing (Prof. Dr.-Ing. Ekkard Brinksmeier)

ZeTeM—Zentrum für Technomathematik: Industrial mathematics (Prof. Dr. Peter Maaß), simulation systems (Prof. Dr. rer. nat. Alfred Schmidt)

The interdisciplinary cooperation between production engineering, mathematics, and physics is an excellent basis for research in the demanding field of micro metal forming. A prerequisite for successful cooperation is the funding of manpower and equipment, which was granted by Deutsche Forschungsgemeinschaft (SFB 747 Mikrokaltumformen) and University Bremen. The authors gratefully acknowledge this support. Further thanks are expressed to Dr. Sybille Friedrich for coordinating the work within the CRC including the preparation of this book.

Bremen, October 2012 Prof. Dr.-Ing. F. Vollertsen

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Contents

Global Variables

Latin

Variable	Explanation
A	Area (mm^2)
a	Distance (mm)
b	Width (mm)
d	Diameter (mm)
E	Modulus of elasticity (GPa)
F	Force (N)
h	Height (mm)
HK	Knoop hardness
HM	Martens hardness (N/mm^2)
k_f	Flow stress (MPa)
l	Length (mm)
p	Pressure (N/mm^2)
r	Radius (mm)
R	Roughness (μm)
s	Sheet thickness/layer thickness/material thickness (μm)
S	Surface roughness (nm)
t	Time (s)
T	Temperature (K)
u	Upset ratio
v	Velocity (mm/s)
V	Volume (m^3)
$\dot{V}$	Volume material removal rate (m^3/s)

Greek

Variable	Explanation
δ	Deflection (µm)
Δ	Difference (µm)
ε	Strain (=$\Delta l/l_o$)
$\dot{\varepsilon}$	Strain rate (s^{-1})
ρ	Density (kg/m^3)
φ	Logarithmic degree of deformation (=$\ln(l/l_0)$)
μ	Friction coefficient
λ	Wavelength (m)
v	Kinematic viscosity (m^2/s)
ρ	Density (kg/m^3)
σ	Normal stress (MPa)
σ_M	Ultimate tensile strength (MPa)
σ_N	Nominal stress (MPa)
σ_{pl}	Yield strength/elastic limit (MPa)
$\sigma_{pl\ 0.2}$	Yield strength with 0.2 % plastic deformation (N/mm^2)
τ	Shear stress (MPa)
ψ	Potential (V)

Global list of subscripts (These subscripts are used globally)

Subscript	Explanation
0	Initial condition
1,2	Condition 1, 2
a	Arithmetic
ax	Axial
BLH	Blank holder
e	Elastic
f	Yield/feed
fr	Friction
F	(de)formation
G	Grain/gravity
la	Laser
max	Maximal
min	Minimal
M	Melting/tensile strength
n	Normal
N	Rated…
pl	Plastic
P	Punch
r	Radius, radial
t	Tangential

Chapter 1
Introduction

Frank Vollertsen

Micro metal forming is a part of the wide field of metal forming. This class of production technology is characterized by:

1. The shape of the workpiece is obtained by the plastic deformation of (predominantly) metallic materials.
2. In most cases the forces on the workpiece are induced by the coordinated action of at least two tool segments.
3. The tools may contain 0–100 % of the desired shape as analogous memory. If the shape is not stored in the tools, the relative motion of the tools has to be controlled to derive a kinematic generation of the desired shape.
4. By definition, there is no material loss in metal forming. In practice however, the preparation of the raw part and finalization of the shape of a workpiece makes some cutting operations necessary, typically incurring material loss of 20–50 %.

The specific aspects of micro metal forming may be seen from a definition by Geiger et al. [1]. In this definition micro metal forming is *the production of parts and structures with at least two dimensions in the sub-millimeter range* by metal forming. Processes for semi-finished products like wire drawing or rolling of foils are not part of micro metal forming (mmf) by this definition, while those processes might entail some of the typical challenges of mmf. To illustrate this definition, it is said that a part made by mmf should fit with a strictly linear motion through a circular hole of diameter of 1 mm. It is obvious that this definition is just a restriction in the size of the parts. Therefore, one may wonder why the well-known processes of (macro) metal forming could not be applied to mmf by just reducing the billet, blank and tool sizes. Specific features of mmf and related products are:

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1. The size or at least one of the dimensions of the produced parts is comparable with the grain size of the material used, resulting in hard to control material behavior.
2. The very small volume of the parts changes the failure behavior due to different probability of the occurrence of a defect in a particular workpiece, if homogeneous defects with low density exist in the raw material.
3. The very low weight (typically between 100 μg and 10 mg) of the (raw) parts make handling difficult due to, for example, adhesion effects. As precise handling is necessary for joining operations, joining is less desirable. Therefore parts should integrate multiple functions to reduce the number of components in an assembly and to minimize the number of handling and joining operations. This results in turn in a more complex design of at least the intermediate stages of the product. As an example, interconnected multiple parts are manufactured as one workpiece, which are separated after assembly to achieve independent electrical functions. On the other hand, the small weight might allow the use of more expensive materials. This is also true for micro forming tools, which may be manufactured from a single crystalline diamond.
4. Quality assurance becomes more difficult compared to macro parts, as many methods usually employed cannot be used for the measurement of micro part dimensions. Also the (scaled down) tolerances interfere greatly with the precision of the metrology, making the use of methods like statistical process control (SPC) impossible.

As the parts are smaller than a grain of rice, there is reference to silicon technology and the question arises whether this technology can deliver the same parts as micro metal forming. A closer look at silicon technology shows differences in at least the following four features:

1. Mmf parts are often larger than those of silicon technology.
2. The variety of materials is much greater in mmf, as many metals can be processed.
3. Parts produced by silicon technology are almost always 2 ½ D, e.g. they have a constant cross-section along a (limited) height (so-called prismatic structures).
4. Mmf may also be economically successful for small lot sizes.

All in all, mmf and silicon technologies should be understood as being complimentary rather than competing technologies.

Mmf is already in use for the production of a few parts for the electronic industry, such as shafts for micro motors or end-caps for SMD-resistors, see Fig. 1.1. The processes which are in use for the production of these parts demanded great efforts for their (mostly empiric) development, making the processes only economically viable for very large lot sizes of some millions or even billions of parts per year. A wider use of the mmf technology class could be achieved, if the production was better planned, processes were more stable and sound control was implemented. This book is intended to be a kind of technological guidance for mmf. There is continuous growth in mmf knowledge by the

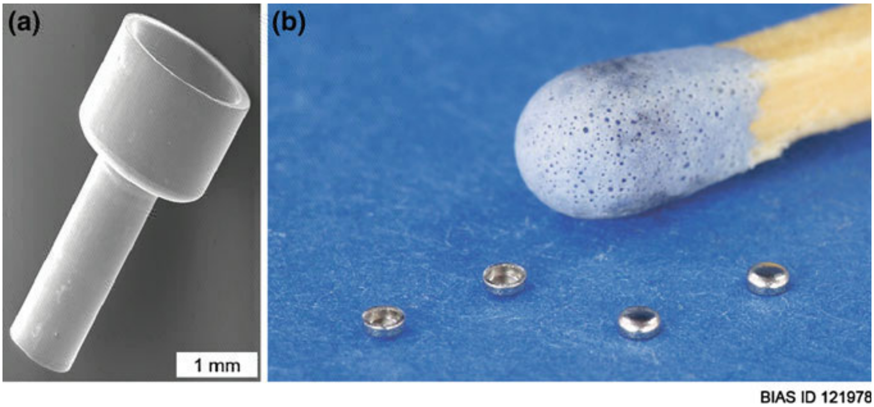

Fig. 1.1 **a** Deep-drawn shaft of a micro motor (18 drawing steps), courtesy of U. Engel. **b** Deep-drawn end caps for resistors, courtesy of Stüken GmbH & Co

further development of parts and processes. Related processes are macro metal forming, silicon technology and high-precision cutting technology, which are already described in detail. This current description should help both the new and the experienced user of mmf decide on the part and process layout for the prompt start of a stable production process.

Reference

1. Geiger, M., Kleiner, M., Eckstein, R., Tiesler, N., Engel, U.: Microforming CIRP Ann. **50**(2), 445–462 (2001)

Chapter 2
Basic Aspects

Frank Vollertsen

Latin

A	Area (mm^2)
A_0	Initial area (mm^2)
A_l	Liquid contact area (mm^2)
A_s	Solid contact area (mm^2)
a	Distance (mm)
b	Width (mm)
d	Diameter (mm)
d_0	Initial diameter (mm)
d_1	Major diameter after deformation (mm)
d_2	Minor diameter after deformation (mm)
d_p	Punch diameter (mm)
E	Modulus of elasticity (GPa)
F	Force (N)
F_{BLH}	Blank holder force (N)
F_E	Electrostatic force (N)
F_{fr}	Frictional force (N)
F_G	Gravitation (N)
F_n	Normal force (N)
F_{vW}	Van der Waal's force (N)
F_γ	Force induced by surface tension (N)
h	Height (mm)
h_0	Initial height (mm)
k	Yield stress in shear (MPa)
k_f	Flow stress (MPa)
k_{fs}	Flow stress at the surface (MPa)
k_{fv}	Flow stress in the volume (MPa)

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l Length (mm)
l_0 Original length (mm)
l_1 Length during deformation (mm)
l_G Grain size (mm)
l_{Na} Length nakajima test
m Friction factor
p Pressure (N/mm^2)
p_l Closed pocket pressure (N/mm^2)
q Wear rate ($m^3 \cdot (Nm)^{-1}$)
s_0 Initial material thickness (mm)
T Temperature (K)
t Time (s)
v Velocity (mm/s)
V Volume (m^3)
w Path (mm)

Greek

Δ Difference (µm)
ε Strain
φ Logarithmic degree of deformation = $\ln(l/l_0)$
$\dot{\varphi}$ Deformation velocity (s^{-1})
φ_1 Major strain
φ_2 Minor strain
Λ Scaling factor
η Dynamic viscosity ($N\ s/m^2$)
κ Grain number
µ Friction coefficient
ν Kinematic viscosity (m^2/s)
σ Normal stress (MPa)
σ_M Ultimate tensile strength (MPa)
σ_{pl} Yield strength (MPa)
τ Frictional shear stress (MPa)
τ_{SC} Shear stress for a single crystal (MPa)

2.1 Size Effects

Frank Vollertsen

2.1.1 Definition and Categories

The term ‘size effect’ is often used when experiments with samples of different size, e.g. different sheet thicknesses in tensile tests, present non-uniform behavior. More than once in the past different behavior has been wrongly referred to as size effect. In one example, tensile stress in foils with thicknesses of 200 and 50 μm was called a size effect, despite the fact that the authors of those papers were aware of the fact that the 50 μm foil showed a stronger strain hardening than the 200 μm foil. This in turn was due to rolling without intermediate annealing. Therefore, one should be aware that not every difference observed in samples of different sizes is a size effect.

A general description of size effects as understood in the scientific context is strongly linked to the theory of similarity. This theory (see e.g. [38] for a detailed explanation) has the central hypothesis that systems will behave similarly if scaling, i.e. changing the size, is carried out according to the rules of similarity. All relevant features like speed, weight, size and so forth must be changed in a fixed relation, e.g. by a constant factor which is called scaling factor Λ. As an example, let us consider a simple upsetting test with the plastic compression of a cylinder of initial height h_0 to the final height h. In order to keep the example simple no friction should occur. The velocity v

$$v = \Delta h/\Delta t = (h_0 - h)/\Delta t \tag{2.1}$$

is the punch velocity and

$$\dot{\varphi} = d\varphi/dt = \Delta\boldsymbol{\varphi}/\Delta\boldsymbol{t} \tag{2.2}$$

is the deformation velocity, where φ is the logarithmic strain

$$\varphi = \ln(h/h_0) \tag{2.3}$$

In the case that h_0 is changed from size 1 to size 2, a similar material behavior (in terms of flow stress k_f) is expected for similar deformation speeds (and identical material, i.e. grain size, predeformation, temperature and so on), e.g.

$$k_{f1} = k_{f2} \tag{2.4}$$

for

$$\dot{\varphi}_1 = \dot{\varphi}_2 \tag{2.5}$$

For identical strain Eq. (2.5) yields when using Eq. (2.2)

$$\Delta t_1 = \Delta t_2 \tag{2.6}$$

As Δh_1 is not equal to Δh_2, v_1 is not equal to v_2. Defining

$$h_{0,1} = \Lambda h_{0,2} \tag{2.7}$$

the relation of punch velocities from Eq. (2.1)

$$v_1/v_2 = \left(h_{0,1} - h_1\right)/\Delta t_1/\left(h_{0,2} - h_2\right)/\Delta t_2 \tag{2.8}$$

will together with Eqs. (2.6) and (2.7) yield

$$v_1/v_2 = (\Lambda h_{0,2} - \Lambda h_2)/\left(h_{0,2} - h_2\right) = \Lambda \tag{2.9}$$

Therefore, if the height $h_{0,1}$ is $\Lambda = 10$ times the height $h_{0,2}$, the punch velocity has also to be increased by a factor of 10 to obtain similar material behavior—at least according to the theory of similarity. In fact this identical material behavior is not observed in small samples, where the grain size is in the order of the sample diameter. Such deviations from the expected behavior are called size effects, which are visible under conditions where the rules of similarity are obeyed.

Size effects are defined as follows [51]: *Size effects are deviations from intensive or proportional extrapolated extensive values of a process which occur, when scaling the geometrical dimensions.* By this definition, size effects are defined as the deviation from the normal, e.g. expected behaviour, of a system. The scaling is further confined to geometrical scaling, which is probably the most important especially for micro technology. Intensive values are—according to the common definition in physical chemistry—system parameters like temperature or pressure and material parameters like density; they do not change with the volume of the sample. Extensive values are volume-dependent parameters like mass. The change in extensive value, e.g. the mass of a sphere, with changing size has to be considered when calculating the size effects. A proportional extrapolation simply means that one has to consider that an increase of a factor of 10 of the radius r of a sphere will increase the mass by a factor of 1,000, as the volume (and the mass, constant density provided) is proportional to r^3. The definition also implies that a size effect can be quantified as a ratio (even a difference could be used) between the value x_1 and x_2.

A systematic approach towards size effects was developed and introduced [50]. This system is based on three main categories of size effect, which in turn are subdivided in subgroups. Having such a system can help analyze existing effects in order to determine which mechanisms are behind a particular behavior.

In Fig. 2.1, the three main categories of size effects are shown. The name of the groups are given by the feature that is held constant during scaling and which is also responsible for the occurrence of the size effect. This method of addressing the different groups of size effects already shows that the scaling process will not change all parameters, since some will be held constant.

At first glance it might appear surprising that a constant density should be the source of a size effect. The common basic principle of those effects is based on the fact that a constant density of features (e.g. voids) also means a constant distance

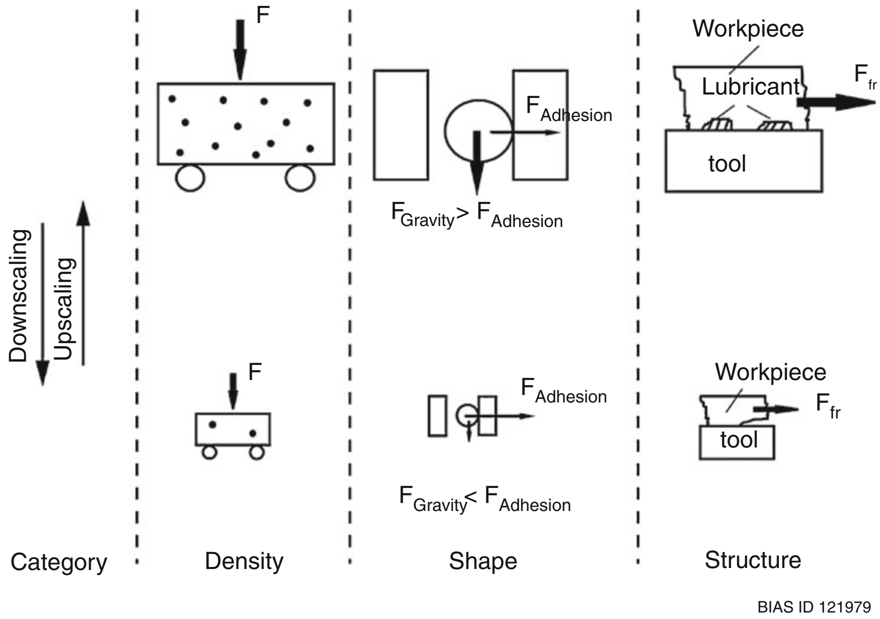

Fig. 2.1 Main categories of size effects, according to [51]

between them. If the sample size is large compared to that distance, the probability of the existence of such a feature in a volume element of the sample will be high. On the other hand, if the sample size is of an order of magnitude equal to the mean feature distance, there may be samples showing no such characteristic feature, which in turn results in the different behavior of the part.

The second category of size effects are characterized by having a constant shape, which addresses the effects produced by the ratio between surface and volume. Many effects used in nano technology are based on the shape size effects, as the relative surface area increases strongly with decreasing size. Consider a catalyst which enables chemical reactions through intermediate reaction phases at its surface. A sphere of 1 mm in diameter has a total surface area of 3.14 mm^2. As the surface to volume ratio scales with a factor of 1/r, the total surface of the spheres with the same total volume but a size of 10 nm will increase by a factor of 10^5 to 314,000 mm^2. The common principle of shape effects is that there are volume related values (in our example: the number of parts) and surface related values (in the example the total surface area) which determine the observed value. The relation between these different components changes with size, which leads to a dominance of either one or the other effect.

The size effects summarized in the third group show a certain similarity to the first category, the density effects. The common source of the structure effects is also the relation between the sample size and the length, this length not being a mean distance between evenly distributed features but a discretely localized distance defined by the atomistic or engineering structure of the workpiece. Again, the size of this characteristic length is held constant, which gives rise to size effects when the sample size approaches the size of the characteristic length.

Returning to the subject of essential mechanisms for the occurrence of size effects, one can conclude that the main source of size effects is the fact that it is not possible to keep the relation between all relevant parameters constant when reducing the size of the parts. As an example, imagine the scaling down of a sheet metal forming process. If one reduces the sheet thickness the relation of grain size to sheet thickness will increase. To scale down every factor, the grain size could be reduced. While this would keep the relation between grain size and sheet thickness constant, the strength of the material would increase according to the Hall–Petch-relationship. The higher strength will have an impact on the elastic deformation of the tools among other effects. Therefore, the correct scaling of all relevant parameters is not possible, and size effects are inevitable. This also leads to a definition of a general mechanism of size effects; this is based on the fact that different subprocesses or force components will have a different relative importance at different sizes. The nature of the processes is that all subprocesses and forces exist in all realizations of different sizes, but depending on the size certain aspects are dominant.

In order to show size effects, experiments with samples of different sizes are necessary. This results in the need for a nomenclature or definition for the size. There is a straightforward designation for size derived from the theory of similarity. To address a specific size of a part, a value called a 'scaling factor' (often λ is used as a variable, here Λ is used) with no dimension is taken. If we take Λ as the value, $\Lambda = 1$ would designate the 'normal' size of the part, e.g. a sheet thickness of 1 mm, while $\Lambda = 0.1$ would refer to a sheet of 100 μm in thickness, as it is intended that the 'actual value = Λ times normal value'. This method to designate the absolute size of a realization has the advantage that Λ can be used as a variable (independent from features like length, surface area, volume or time) in formulas and graphs, if trends with variation of the size are shown. On the other hand, some information is lost using such relative values. One always needs calibration with respect to the 'normal value'. In the given example the information '$\Lambda = 1$ means sheet thickness = 1 mm' describes this normal value. Without this information about the normal value it is difficult or impossible to know in which case size effects occur. Due to this, throughout this book the nomenclature introduced in [53] of 'size<nn>' will be used, where '<nn>' is the initial sheet thickness or the rod diameter in μm. As an example, 'size20' designates a sheet with a thickness of 20 μm or a wire with a diameter of 20 μm. The example given above (a realization of $\Lambda = 0.1$ with a standard value of 1 mm) would be identified by 'size100'. Using 'size<nn>' for designating a workpiece realization always contains the information that samples are produced by correct scaling, e.g. reducing as far as possible all relevant features by the same factor.

As the material behavior under plastic deformation is essential for micro forming (and also for the explanation of size effects), the grain size, and especially its dimension relative to the sample thickness, plays an important role. Due to that, a variable κ, which is called 'grain number' is introduced. The grain number κ is defined as the (average) number of grains (having a grain size of l_G) along the thickness s_0 of the sample, e.g. the initial sheet thickness:

$$\kappa = s_0/l_G \tag{2.10}$$

So, for a grain size of 10 μm and a sheet thickness of 50 μm a grain number of 5 is obtained. The grain number can become also less than 1, if the grain size, measured in the sheet plane, is bigger than the sheet thickness. A sheet microstructure with a grain number less than 1 is also called a 'Tiffany structure'.

Very often it is argued that size effects are detrimental and must be avoided. This is not true, as will be shown by the examples in Chap. 6 where processes are discussed which are enabled by size effects. The use of size effects can also be seen from the strength measurement of materials. This also demonstrates the large variety of size effects. Figure 2.2 is a summary of different work on size effects affecting the strength of materials. On the x-axis the absolute size of the parts or the relevant area covered by the measurement principle is given. Essentially for larger samples this is the rod diameter or sheet thickness of the samples. In small dimensions, this size in given by the indentation depth, as strength measurements on samples in the nanometer dimension are often made by indentation hardness measurements. It is worth noting that size effects appear in a wide range of sample sizes, covering 6 orders of magnitude. On the y-axis a more complex value is used. It is called effect strength and defined (see [50]) to demonstrate the significance of the size effect, e.g. how strong the effect changes the observed value. Essentially, the effect strength is the ratio between the change in the value (here the strength of the material) with change in the size, while per definition the effect strength is always a positive value. In some cases, 'smaller is stronger' is true, but there are also cases in which 'smaller is weaker' applies. In both cases the effect strength is positive. It is obvious that size effects concerning the strength of materials which occur in very small parts are much stronger than those occurring in large parts. This emphasizes the importance of the consideration of such effects in mmf.

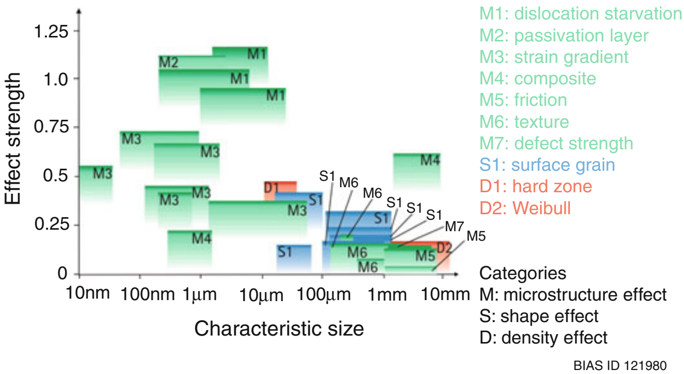

Fig. 2.2 Effect strength of different size effects affecting the flow stress, according to [51]

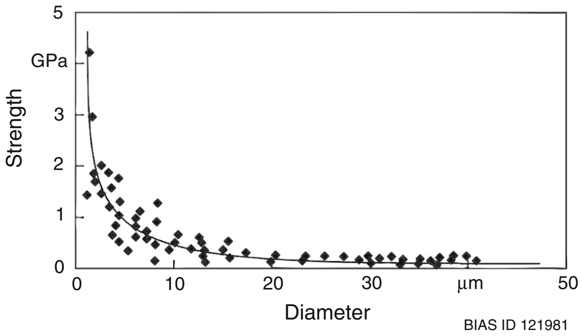

Fig. 2.3 Strength of copper whiskers, according to [51], data from [34]

In order to demonstrate what size effects mean to the strength, some values from experiments using whiskers are replotted in Fig. 2.3. It demonstrates the strong increase in the strength of pure copper, normally known as a very soft material, up to values far above the strength of modern high strength steels. The effect is due to the fact that the sample diameter falls below the average distance between dislocations. Due to that the strength is not determined by the dislocation movement, but by the theoretical strength defined by the cohesion of the atoms within the lattice.

2.1.2 Density Effects

A density effect is a size effect which occurs during scaling when keeping the density of a feature constant. In particular, density effects will occur when the actual part size approaches the mean distance between the features. The density effects are subdivided by the three categories of the possible appearance of (microstructural) features. Those can appear as points (e.g. pores), lines (e.g. dislocation lines) or areas (e.g. grain boundaries). In the case of known size effects, there is a homogeneous distribution of such features though the volume of the part, while it cannot be excluded that a distribution of such features at the surface could also lead to density size effects.

The first possible feature shape shown in Fig. 2.4 is the point feature resulting in the point density effect. Those point elements can be pores in brittle ceramics or metallic welds, but also foreign atoms in a matrix lattice. The best known example of a point density effect is the so-called Weibull effect, which describes the size dependence of samples with low but not vanishing porosity. In large samples, pores near the surface give rise to stress concentrations and therefore they determine the strength of the part. Smaller samples may show no pores in the highly loaded region, because the density and therefore the distance between the pores is kept constant. Due to that, the probability of finding no pores within the critical region is increased, this results in the higher strength of smaller samples made from identical material.

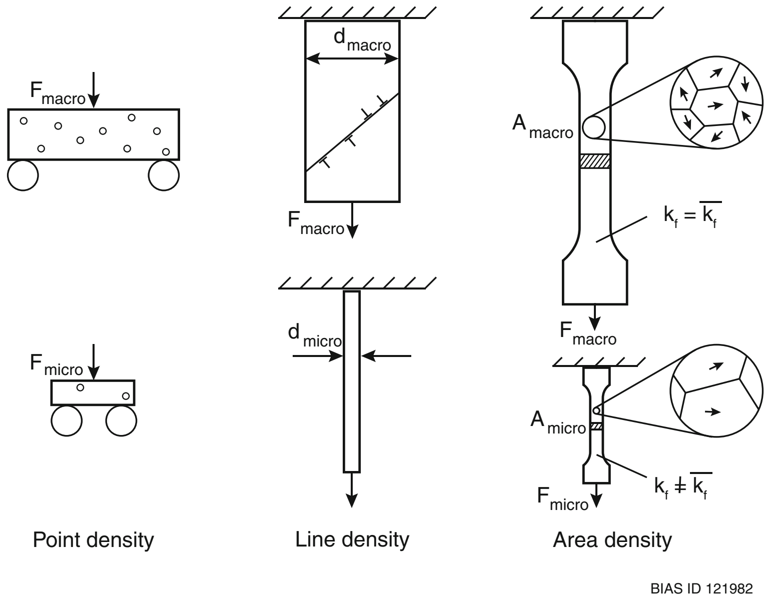

Fig. 2.4 Subcategories of density effects

The line density effect can be observed in the case of copper whiskers, see Fig. 2.3. The line density is given by the initial dislocation density of the samples, which is typically 10^6–10^8/cm^2, corresponding to a mean distance of 1–10 μm of the dislocations. Crystals with a diameter below 10 μm tend to have no (mobile) dislocations, resulting in a transition from deformation via dislocation movements to other mechanisms, which are dominated by the interatomic forces. This results in a very strong increase in the strength.

The third subgroup of the density effects in Fig. 2.4 is that of area density effects. The density of interfaces can be kept constant by maintaining a constant grain size. Sometimes the area density effects are determined by another layout of the experiments. Instead of decreasing the size of the samples at a constant grain size, the grain size is changed while the size of the samples is held constant. One should bear in mind that this is not the same. Despite the fact that the grain number can be changed by a layout such as the one in the experiments, the grain boundary density is not held constant, giving rise to additional effects like changes in strength according to the Hall–Petch-relationship. This must be accounted for if any forces or elongation limits due to plastic deformation are relevant. In some cases, experiments from such a layout can give interesting information. An example can be seen in Fig. 2.5 for extruded parts, with an initial grain number of 24 and 4. If only a few crystals exist along the cross-sections of the samples ($\kappa = 4$), the individual orientation has a strong impact on the local flow stress and in turn on the flow velocity. Those differences in the material flow are the source for the heavy distortion of the micro samples, which does not occur at a larger grain number ($\kappa = 24$).

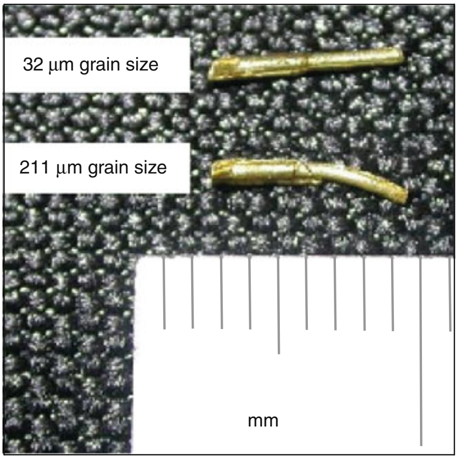

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Fig. 2.5 Workpiece distortion as a result of density effects [30]

2.1.3 Shape Effects

Shape effects are such effects that occur if a process, assembly or part is carried out in a bigger or smaller realization with the same shape but different size. The easiest example is two spheres of different diameter. All these effects are based on the change in the surface to volume-ratio, which occurs during this kind of scaling. According to the general layout of the categorization of size effects, the reason for the size effects must be linked to the particular feature. Of course, in the experiments for density or structure effects the ratio of surface to volume will also change, but it is not essential for the observed size effect in these cases. On the other hand it cannot be excluded that density effects (and/or structure effects) and shape effects occur in parallel and sum up or eliminate each other. Experiments on size effects have to be checked carefully for such biasing effects.

Shape effects are also a very good example for the general size mechanism effects which are given above. This is due to the fact that shape size effects usually occur when the relation between surface and volume determined effects change, as the relative amount of the surface increases with decreasing size. Consider a cube with edge length l, then the volume V will be

$$V = l^3 \tag{2.11}$$

while the total surface area A is

$$A = 6\,l^2 \tag{2.12}$$

The surface to volume ratio is

$$A/V = 6/l \tag{2.13}$$

e.g. it will increase 1/l with decreasing size.

Effects, forces or features which are dominated by the volume are the:

1. Mass of the part and all features which depend on it, such as

(a) heat content
(b) weight
(c) acceleration forces
(d) distances inside the volume, e.g. relevant for heat transfer by conduction

2. Amount of features in the particular volume, like

(a) number of grains
(b) number of pores
(c) amount of absorbed material

On the other hand, the surface is relevant for

1. Surface tension
2. Heat transfer (e.g. heat loss) by convection and radiation
3. Friction effects
4. Number of features at the surface, like

(a) grains with one boundary at the free surface
(b) amount of a adsorbed material
(c) electrical surface charge by electrons
(d) number of atoms, e.g. relevant for van der Waals forces.

Therefore, typically extensive variables are sources of shape size effects, while intensive variables might be the affected value. As an example, one could consider a hot forming process using raw parts heated to a homogeneous temperature in an oven. During the transport the parts will cool down by heat loss due to convection and radiation. The final temperature (an intensive variable) of the part just before the forming process will be determined by the heat content (one volume determined extensive variable) and the heat loss (surface determined extensive variables). With decreasing size the heat loss will become more and more significant, making the control of hot forming for micro parts very difficult.

Shape size effects, caused by a dominant volume or surface effect, might be the result either of concurrent or competing sub-processes. If the sub-processes principally point towards the same direction, e.g. they are concurrent, shape sum effects might occur. One of the most important shape sum effects for micro forming is the change in flow stress with changing size due to the influence of so-called surface grains [36]. As shown in Fig. 2.6, all grains of the microstructure will cause a positive contribution to the macroscopic measured flow stress. If we consider homogeneous grains with respect to chemistry and structure, the contribution will depend on the orientation of the individual grain relative to the loading direction and on the restrictions against deformation of the individual grain. This restriction is high at boundaries with other grains, while it is very low at free

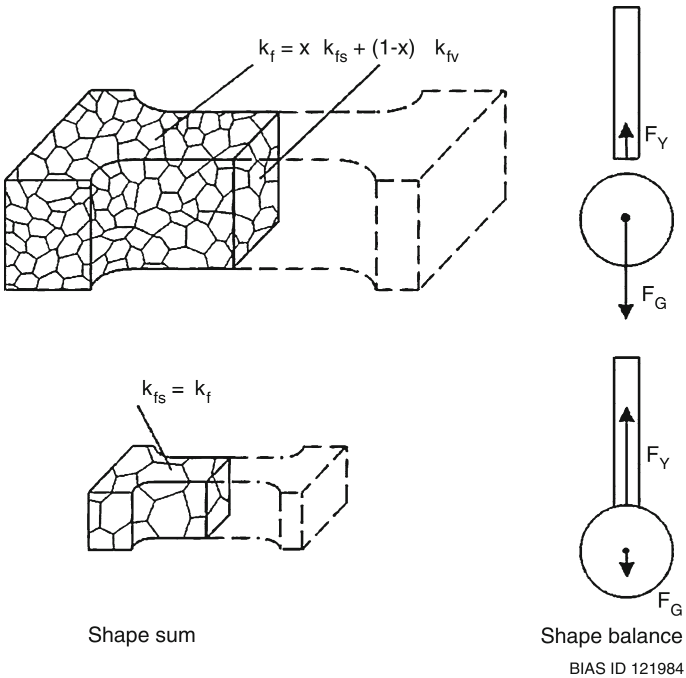

Fig. 2.6 Subcategories of shape effects

surfaces. The effects of the orientation may average out (if not the increase in scatter is a density effect, as the number of grains, not the surface to volume ratio, is relevant to that), while the influence of the softer surface grains will lead to a softer behavior of smaller samples, as the relative amount of the surface grains is proportional to the surface to volume ratio.

Shape size effects, where at least two forces or features act against each other, are called shape balance effects. The most prominent example of a shape balance effect is the problem of workpiece adhesion at grippers, which means some new strategies are necessary for part handling.

Figure 2.7 addresses that problem using a sphere as an example. There are three force components which hold the part at a gripper, while the gravitational forces act as the detaching force. The gravitational force is dependent on the mass of the part and is therefore a volume dependent force. The adhesion force, the van der Waals force and the electrostatic forces are dependent on the surface area and help keep the part on the gripper. While for large parts (far greater than 1 mm in the example shown in Fig. 2.7) the gravitational force is dominant, a decreasing size will lead to adhesion, increasing the necessary relative forces for detachment with decreasing size. If the size drops below 10 µm, even the small electrostatic forces can inhibit the detachment induced by gravitational forces. The role of adhesion is

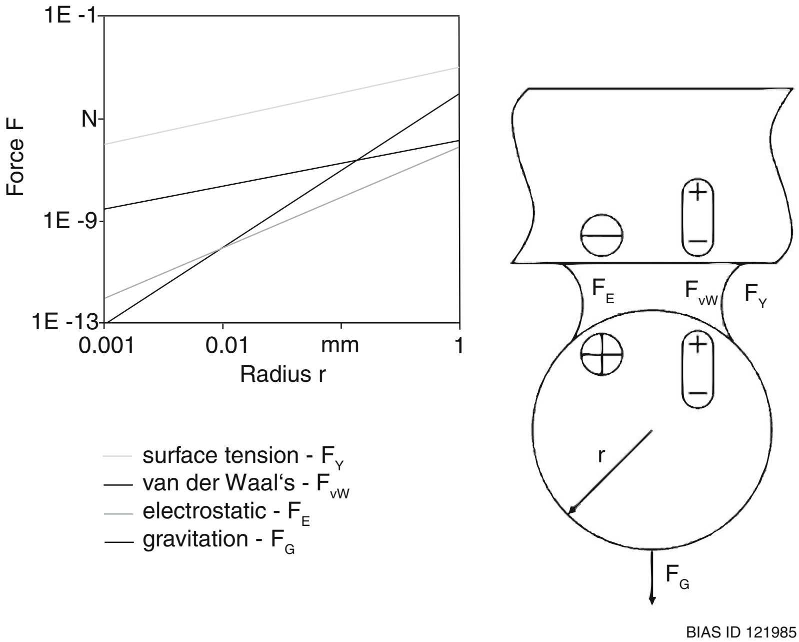

Fig. 2.7 Adhesion problem as a result of shape balance effects

very strong in the given example, as the existence of a liquid film between the gripper and part is assumed. In the case without a liquid layer, the adhesion forces will be much smaller.

2.1.4 Structure Effects

Within this context the term 'structure' summarizes the geometrical structure, e.g. the surface roughness or the geometry of a cutting edge on a cutting tool and the (atomistic) micro structure of the materials, e.g. the dislocation pile-up at a boundary or the texture of the grain orientation. Structure effects are those size effects which typically occur if the structure is held constant and a characteristic value of the part (e.g. sample thickness) approaches the characteristic length of the structure (e.g. length of a dislocation pile-up).

The first subcategory of structure effects is the characteristic length. A characteristic length is defined by the microstructure of the material, e.g. the length of the pile-up at a grain boundary, the width of a stress field around a precipitation (defined by a threshold value for the stress). The characteristic length in the strain gradient plasticity is also a characteristic value. For the example shown on the left hand side

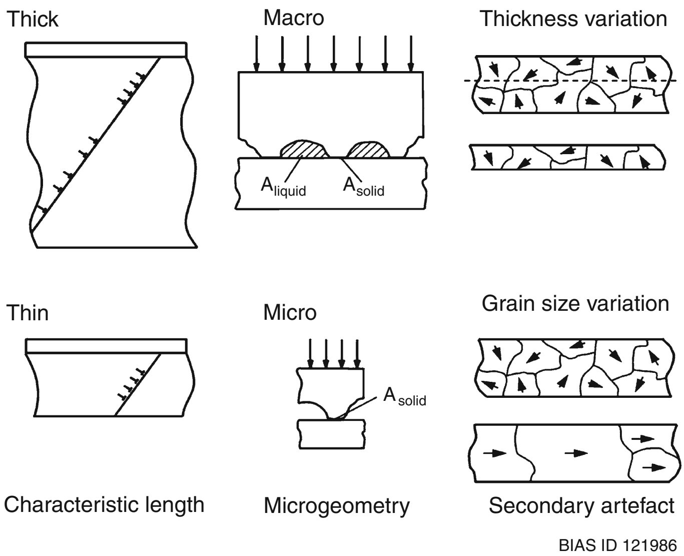

Fig. 2.8 Subcategories of structure effects

in Fig. 2.8, the length of the pile-up necessary to break through a hard surface layer is the relevant value. If the sheet thickness approaches this length of the pile-up, which happens at sheet thicknesses of some μm, the dislocation motion of any dislocation will be influenced by this layer, increasing the necessary stress for the movement of dislocations. This is measured macroscopically as an increase in flow stress. If the sheet thickness is increased, there will be areas in the sample which are outside the reach of the surface coating; e.g. the dislocation will move without any effect of the pile-ups at the surface layer, the sample appears to be softer.

It should be noted at this stage that, if one tends to argue that the Hall–Petch effect is also a structure size effect as it is also based on the consideration of dislocation pile-ups at grain boundaries, one should keep in mind that the Hall–Petch relation essentially describes the changes in strength with changing grain size for samples of constant size. Therefore, the Hall–Petch effect is not a size effect at all within the general definition of size effects, as the change in the macroscopic size of the workpiece is not necessary to obey the Hall–Petch-effect. Despite of this, experiments must be designed very carefully to avoid biasing effects from Hall–Petch effects in experiments on size effects. The latter is especially true for experiments where the grain size plays an important role and which are often analyzed using different grain numbers and constant thicknesses as explained at the end of Sect. 2.1.2.

Effects of the characteristic length cannot be avoided, as there is no possibility to change the characteristic length by the experimental set up. This is the case because the characteristic length is fixed by the nature of the material. In microgeometry effects this is not the case at first glance. Microgeometry effects are