Size effects in manufacturing of metallic components

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1. Introduction

Rules for up- or down-scaling are extensively used in fluid dynamics, enabling experiments with smaller samples, which are cheaper and much easier to conduct than real size experiments. The theory of similarity describes the conditions which must be satisfied for a successful up- or down-scaling for that purpose. Pioneering work in this area was done by Pawelski [1,2], who worked on the rules of similarity with respect to metal forming, reportedly the earliest [3,4]. It was shown that the rules of similarity can help to design proper experiments, for example, for compression testing with lubrication [5]. But, due to the complex nature of processes such as metal forming, Pawelski comes to the conclusion that it is often not possible to obey all necessary rules of similarity when up- or down-scaling a process [6], while the results of those limitations lead to so called size effects. A recent research work illustrates such effects in solid metal processing through simulation [7].

Microtechnology is very prominent field where size effects play an important role. Reviews on micro forming highlight the importance of size effects in this field [8,9], where long-term basic research is required to realise industrial applications [10]. Also in the assembly of micro systems, size effects are one of the problems to be solved [11]. Also, it is evident from the recent review on micro machining [12] that no major effort has been made relating size effects, and no recent interdisciplinary review on size effects was reported since then. The aim of this paper is to comprehensively review the work done with respect to size effects.

2. Basics

2.1. Definition

In order to establish the contents of this paper, size effects need to be defined first. This is done as proposed in [13] as follows.

Size effects are deviations from intensive or proportional extrapolated extensive values of process characteristics which occur, when scaling the geometrical dimensions.

Size effects occur due to the fact that the ratio among all decisive features cannot be kept constant according to the process requirements [13].

Intensive variables are those which do not change with the mass, for example, temperature, density, etc.

Extensive variables are those which change with mass, for example, heat content, inertia force, etc.

Scaling means to reduce (down-scaling), or increase (up-scaling) all relevant length dimensions of the workpiece, the tools, and/or the processing parameters in a geometrically similar way, i.e., by a constant factor.

Geometrical dimensions might be workpiece, tool and/or geometrical process dimension(s).

Size effects can be beneficial, neutral or detrimental. Despite the fact that such size effects can occur in all manufacturing processes, this paper is limited to metallic parts and those processes, which are based on plastic deformation, i.e., metal forming and machining. It is also emphasized by the definition that size effects are of somewhat surprising nature at the first glance, as they occur despite the fact that the length relationship between all geometric features are held constant.

2.2. Typology

One early approach for a typology, e.g., a systematic order of size effects in manufacturing is given in [14]. An update was given
in [7] by defining systematically the sources of the size effects. This approach was recently revised [13], and the result is given in Table 1. The classification is made into three categories, which are in turn divided into subgroups.

The basic approach of the typology is to characterize the effects using the kind of value, which is held constant during scaling and is responsible for the effect. Based on this, density, shape and (micro) structure effects can be distinguished, see Fig. 1.

Density effects occur, if the density – as an intensive variable – is held constant during scaling (up or down). Three different kinds of density can be distinguished, as the feature can be an interface area, a line or a point. For example, consider a constant defect density, e.g., pores, in a brittle material. In big samples, there will be a large (absolute) number of such defects, resulting in low and constant fracture strength. But, if one prepares very small samples from the same material, some samples will contain no defect, while others will contain one, resulting in a considerable difference in the strength and scatter in strength between the big and small samples. This effect is well known, and is described by the Weibull distribution.

The category of shape effects comprise such effects that occur due to the fact that the volume of a part is proportional to the third power of its size \( r^3 \) while the surface goes with the second power \( r^2 \). Changing the size \( r \), while keeping the shape constant, would result in an inevitable change in the relation of surface to volume by \( 1/r \). All effects which are based on volume-related and surface-related values are summarized here. The two subgroups of this category, distinguished by these effects, were the volume-related values which are concurrent to surface-related ones (i.e., shape balance effects), and those where the observed value is a sum of volumes defined and surface defined sub values, while the relative amount of the two change due to scaling (shape sum effects). One example of a shape balance effect is the size effect in handling, for example, the sticking effect described in [11].

This size effect, which makes it difficult to release small parts from grippers, is due to the change of the relation (the balance) between the surface-determined adhesion forces and the volume-determined gravitational forces.

The group of microstructure effects comprise such effects which occur due to the fact that it is (in practice) impossible to scale all structural values simultaneously by the same factor. This group can be subdivided into three categories, which distinguish between those effects, where it is physically not possible to change a characteristic length, where it is not practised to scale the micro geometry and where secondary artefacts occur while trying to scale in an appropriate way. One size effect of the characteristic length type is the limited validity of the Hall–Petch relationship, described in [15]. The grain size is the three-dimensional feature, which is scaled down, while the diameter of dislocation loops is the characteristic length. As explained in [15], the Hall–Petch relationship is not valid in copper below a grain size of about 50 nm, as dislocation loops cannot be scaled down to such a grain size. Further details about the typology are given in [15].

3. Flow stress

3.1. Experimental findings

3.1.1. Methods for scaled strength determination

The measurement of the flow stress in scaled experiments, for example, when the sheet thickness or rod diameter is reduced, can become very difficult in the micro range, as the handling of the small samples tends to introduce distortion and therefore uniaxial stress conditions are difficult to guarantee. Furthermore, machines are necessary which allow the adaptation of the loading parameters (e.g., speed) to the sample size. One solution for such a machine, which can be used for different types of tests, was developed and described in [16].

As tensile tests might become difficult, plane-strain upsetting tests using stacked sheet metal samples were evaluated [17]. It was seen from the results that the kind of sample type (loosely stacked sheets or glued sheet packages) strongly influenced the result, while the number of layers showed no significant influence on the measured flow curve [17]. If the same annealing condition is applied to the material before the test.

Due to edge effects an increase of the flow stress with decreasing sample width was sometimes observed. In order to exclude such effects, the bulge test was investigated for scaled flow stress determination. Picart et al. [18] used a hydraulic bulge test with two different die diameters (20 mm and 50 mm, respectively), which were held constant during testing of different sheet thicknesses. They showed that there is a significant influence of the die diameter on the measured flow stress [18]. Kurosaki used scaled tool dimensions for hydraulic bulge tests on copper foils having a thickness between 5 \( \mu m \) and 1 mm [19]. He showed that

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Fig. 1. Categories for size effects [13].
for those experiments the Hall–Petch relationship was still valid. A new method for the determination of flow curves for micro specimen, the Aero-Bulge test, was introduced by Hoffmann et al. [20]. Here the flow curve is measured by pneumatic bulging of the foil, while the flow stress can be calculated from the applied pressure and the shape of the sample as in hydraulic bulge tests. It was pointed out that the flow curve determination is much more precise than that from tensile tests.

Micro hardness tests can be used also as a measure for the flow stress, as it was shown by Chen et al., for a CuZn alloy, where a relationship between flow stress \( k_f \) and hardness \( H \) like

\[
k_f = \frac{H}{3}
\]  

was found [21]. The tests were made with a test load of 1 N. Other results for copper show that also for nano-indentation with loads down to \( 3 \times 10^{-3} \) N, a good correlation can be found between the tensile strength of whiskers and the strength calculated from hardness tests [22].

A method which is especially developed for thin samples such as foils down to some \( \mu m \) in thickness is the bending and unloading test. Provided that the Young’s modulus of the material is known, the strength at a certain strain can be determined just from the measurement of the curvature after unloading [23]. Different strains can be achieved by mandrels having different diameters. Due to characteristic length effects (see Table 1) differences occurred between the results from tensile tests and from bending tests.

### 3.1.2. Influences on the mechanical strength

Size effects on the strength of metallic material (pure metals and alloys) were investigated in a wide range of sizes, which covers 6 orders of magnitude. It seems that neither the material itself (pure nickel, gold, aluminium; brass, aluminium alloys or high alloyed steel), nor the shape of the samples (sheet, wire or rectangular blocks) is of primary meaning for the results. The most important feature is the size range [13].

In Fig. 2 an overview of the extent of different size effects is given. While the \( x \)-axis shows the range of the characteristic size (typically, the sheet thickness or the wire diameter, but also indentation depth) of the samples used for the particular investigation, the \( y \)-axis reflects the maximum relative importance of the measured influence, the influence strength \( I_i \). This influence parameter is defined as [13]:

\[
I_i = \frac{(X_{\text{max}} - X_{\text{min}})}{(X_{\text{max}} + X_{\text{min}})} \frac{(l_{\text{max}} - l_{\text{min}})}{(l_{\text{max}} + l_{\text{min}})}
\]

while \( X \) are the measured values (flow stress, yield stress, coefficient of friction, etc.), \( I \) is the characteristic length, and ‘min’ and ‘max’ denote the minimum and maximum values, respectively. The maximum relative importance \( I_i \) shows the importance of the effects, as it accounts for the fact that the differences in mechanical strength could be small, but the range of sizes might be also small, see e.g., [24], where a strong influence is seen, while other investigations with wide ranges of sizes show only little effects (see e.g., [19]).

It was surprising that the analysis shows almost always clearly separated fields for the most important size effects. A scientific explanation for the reduction of the maximum effect strength with increasing characteristic size cannot be offered here. It seems to be obvious that a certain effect shows certain strength and appears in a certain size span. Despite the fact that it is not fully unambiguous, Fig. 2 is a kind of map which would help to identify size effects from experimental findings. It also shows whether there is the probability for an interaction of different effects. As the Hall–Petch effect occurs in a similar size span like the surface grain effect, but is much stronger, experiments concerning the surface grain effect must carefully exclude the occurrence of the Hall–Petch effect, normally by working with a constant grain size. The interference with Hall–Petch might be the reason, why in some published work the surface grain effect was not detected despite the fact that a wide span from 5 \( \mu m \) to 1 mm in sheet thickness was investigated [19]. Unfortunately, in that study the grain size was not constant for the various sheet thicknesses, but decreased steadily.

The composite effect, the strain gradient plasticity and the surface grain effect will be explained in more detail in Section 3.2. The dislocation starvation effect denotes a very strong effect which is especially seen at the strength of whiskers, but not limited to that. Whiskers are known as single crystals having no mobile dislocations. Due to this, the strength of real whiskers is very high and approaches the theoretical shear strength (see e.g., [25]). On the other hand, as shown in Fig. 3 (data from [22]), the strength drastically drops with increasing size. A similar effect was seen in compression tests on gold cylinders having a diameter from 300 \( nm \) to 7.5 \( \mu m \) [26]. It can be explained by a dislocation starvation model [26] which basically says that there is a dislocation movement without dislocation multiplication inside the sample. Dislocations have to be generated at the free surface and travel through the whole sample, leaving the lattice at the free surface on the opposite side without any dislocation multiplication, as the travel distance in small samples is smaller than that necessary for reproduction (which is about 1 \( \mu m \) for silver). As dislocation generation at free surfaces needs high stresses, the strength of samples being smaller than 1 \( \mu m \) increases significantly.

In some work (see e.g., [20,27–29]) on the surface grain effect it was surprising that the strength increased with decreasing size, as opposed to what was observed from the surface grain effect, see Fig. 4. This effect, which occurs for samples having a thickness less than the grain size, is qualitatively explained by the texture generated during the preparation of the samples and the influence of the individual grains on the measured strength [30,31]. Based on this, it is called texture effect in this paper. It is assumed that the recrystallization leads to a grain orientation which shows a higher strength than the average orientation in a polycrystal [28]. While the data from Di Lorenzo et al. and Raulea et al. in Fig. 4 have been measured by using a variation of the grain size by recrystallization, the data by Gau et al., which were essentially...
generated from samples with different thickness, do not show the texture effect.

The defect strength effect was observed in an investigation of composite samples due to the fact that the severity of strength determining defects was increasing with increasing sample size [32]. Despite the fact that the maximum relative importance and the size range are nearly the same, the defect strength effect must not be mixed up with the well-known Weibull effect on the strength of materials having statistically distributed defects. The Weibull effect is based on the fact that the probability for the occurrence of a large defect, which determines the strength, increases with the size of the part, as for a constant density of defects, the absolute number of defects in a volume $V$ increases with $V$ (see e.g., [33] p. 77).

The friction effect [34–37] is a typical microstructure effect from the micro geometry, especially the surface roughness. As shown by [37], the coefficient of friction increases with decreasing size, resulting in an increased influence of the friction on the measured flow stress.

3.2. Description of size-dependent flow stress

3.2.1. Composite model

The influence of the processing steps in sample preparation were measured and empirically analysed by [38]. Samples from pure aluminium (Al 99.999) were prepared by different methods (laser cutting, shear cutting, grinding) and partly ground prior to tensile tests. As shown in Fig. 5, the yield strength significantly increased in the cutting process, while the influence increases with decreasing sample width. A similar effect was found by [20]. The difference between the samples of different width disappears with increasing strain during tensile testing. The size effect was explained by the strain hardening of the edges due to plastic deformation by the cutting process (in laser cutting, the shielding gas pressure is responsible for that deformation). The thickness of the affected surface layer is almost constant, e.g., not dependent on the sample size (e.g., width). An analysis, based on a rule of mixture (Taylor averaging model) showed that the yield stress in the deformed edge regions increased by a factor of up to 3.5 which results in the reported manufacturing-induced size effect (see [38]).

Despite the fact that most examples for composite models demonstrate a decrease in strength with increasing size, there are also examples for the increase of strength. The hardness of sapphire was shown to be dependent on the penetration size, but not as expected from the strain gradient theory with a decrease, but an increase of hardness was found with increasing indentation depth, see Fig. 6 [39]. It was explained by a soft layer built in the surface. It was also shown that the preparation of metallic samples has a strong influence on the measured dependence of hardness on the indentation depth [39].

3.2.2. Passivation layer model

In the case of very thin hard layers, strong size effects can occur even if the measured strength is corrected with respect to the effect described by the composite model (i.e., the strength of the hard layer was subtracted from the measured value of the composite). As shown in Fig. 7 the passivation layer leads to a large increase in the strength. This influence was the strongest one within all effects reported here, see Fig. 2.

The increasing difference in the yield stress of passivated copper films compared to unpassivated ones is explained by a dislocation blocking mechanism at the passivated surface [24]. As this is a short-range interaction between the passivation layer and the dislocations inside the copper film, the difference between passivated and unpassivated films disappears for film thickness above 1 µm. Over a half century ago, this effect was anticipated as explanation for the strength of aluminium single and bi-crystals [40], but due to the size of their samples being some millimetres in thickness there is some doubt that the theory was applicable to this case.

Fig. 4. Influence of sheet thickness to grain size on the strength (yield strength $R_p$, tensile strength $R_m$) for aluminium (data from [28,30,31]).

Fig. 5. Technical stress–true strain curves of Al 99.999 after laser cutting (by courtesy of [38]).

Fig. 6. Increase of hardness with penetration depth for sapphire. The sample was exposed to water and tested under a water film (data from [39]).

Fig. 7. Strength of copper films having a thickness $h$ of 0.34 µm up to 4.2 µm with ('passivated') and without hard coatings (by courtesy of [24]).
3.2.3. Strain gradient model

One of the big disadvantages of conventional methods to describe the local flow stress is that the models predict a uniform flow stress, which depends only on the (homogeneous) strain, strain rate, temperature, but does not account for any strain gradients. Therefore, the description of processes having high local strain gradients, such as the deformation at crack tips, the indentation of a cutting tool tip or the torsion of thin wires is extremely difficult, if not impossible. The description of the size dependence of hardness on the indentation depth became the benchmark for theories related to the strain gradient model. Nix et al. [41] give a good introduction to the development of the strain gradient model by Ashby [42], Fleck and Hutchinson [43, 44], while Bazant et al. published a comprehensive review on the development of the strain gradient models [45].

The basic approach of the strain gradient models is that they define two groups of dislocations, the geometrically necessary dislocations (GND) and the statistically stored dislocations (SSD). The SSD are those which are accounted for in conventional models. They are produced during plastic deformation and are stored homogeneous when looking from a macro scale, but statistically distributed on the micro scale. Depending on the process, GND are necessary to accommodate for strain gradients, the easiest example is plastic bending of a sheet, where large deformation is introduced near the surface and no plastic deformation occurs in the neutral layer. To accommodate such strain gradients, GND are stored in the lattice having a distribution according to the strain gradient. The interaction width of the GND with mobile dislocations is described using length scales. For example, Zhao et al. [46] report length scales for six different materials (Al, Ag, Ni, Cu, α-TiAl and γ-TiAl, with length scales of 2.8 μm, 6.2 μm, 4.3 μm, 1.1 μm, 74 nm and 49 nm, respectively), while [41] found length scales of 12 μm and 5.8 μm for annealed and cold worked copper. The differences between the values are not only due to the material, but also due to the different theories. As the mobile dislocations interact with GND and SSD in the same manner, and based on this, plastic deformation within materials having strain gradients can be described properly.

To simulate micro forming with consideration of size effects, the theory of strain gradient plasticity was used in FE-simulation for forming of thin sheet, improving the efficiency of the simulation [47, 48]. Further improvements were achieved by combining a strain gradient elasto-plastic model and a surface grain model. It is concluded that the surface grain model helps to describe the integral forces, while the – concurrently applied – strain gradient plasticity approach removes the sensitivity of the model on the FEM element size [49].

Based on the Fleck–Hutchinson strain gradient plasticity theory, a finite element method was used to predict the indenter size dependent hardness [50]. A nonlocal micromechanical damage model based on the strain gradient plasticity was used for FE-computation of plastic deformation to predict the failure behaviour of a vessel steel [51].

3.2.4. Surface grain model

The surface grain model describes a size effect which is a typical shape sum effect, as it occurs due to the fact that the measured flow stress of a sample is the sum of the share of volume grains and surface grains. When changing the size of the sample while keeping the shape (and the grain size) constant, the share of surface grains increases, which results in decreasing flow stress with decreasing sample size. Surface grains are those which have at least one grain boundary on a free surface, volume grains are those which are in contact with other grains at all its grain boundaries.

First systematic results with respect to micro forming were given by Geiger et al. [52], showing a strong influence of the sample size on the flow stress. A systematic description of the effect was proposed by Kals et al. [53] by defining a quantitative value for the share of surface grains. An empirical formula for the flow stress in dependence on grain size and scaling factor was proposed [54], but despite the fact that the calculated values correlated well with the experimental ones, this model had the typical weakness of empirical models as the influence of surface grains was only accounted for by using experimental data. As the share of surface grains is dependent of the geometry of the cross-section, differences for the flow stress of flat and rod specimens are expected. It is shown qualitatively that such differences exist. If one plots the data from [53], such as shown in Fig. 8, the clear influence of the surface grains can be seen.

Using the size-dependent flow stress, a better correlation between experimental and numerical results can be achieved [53], which is also emphasized by other authors [55]. A model based on the assumption of soft surface areas according to the surface grain theory was demonstrated to enhance the FEM simulation in bulk metal forming [56]. It must be emphasized that the reduction in flow stress with decreasing size due to the surface grain effect must be carefully applied in calculations for forming processes. In bending processes, the surface layers exhibit higher strains than the core layers, which led to the conclusion that the local flow stress, instead of a mean flow stress, should be used in FEM calculations [57]. In the case of tool contact, the effect of the surface grains also disappears. Due to this, no surface grain effect is observed in extrusion (nearly full contact at all surfaces), while in plane-strain upsetting only a smaller fraction of the surfaces compose free surfaces, thus, reducing the influence strength to less than 0.1, which can be seen from the results in Fig. 2 of [58].

3.2.5. Transition areas

There are two very important transition areas to be looked into in modelling, as a change of the most important effect can occur there. The related effects for the first transition have been described in an early paper by Armstrong [59], who additionally pointed out some effects on scatter. If one starts with a large polycrystalline sample, the material might be described as homogeneous and continuum. For the strength of the material, the Hall–Petch relationship can be applied. Reducing the size, for example, going from the right to the left in Fig. 9, the first transition occurs, when a characteristic length...
approaches the grain size. The material behaviour changes from polycrystalline to single crystalline behaviour. A drop in flow stress and, due to readability not shown in Fig. 9, an increase in scatter can be noted. Further reduction in the sample size will lead to a second transition area, where the material behaviour has to be described on an atomic level, and not as a single crystalline material. According to Fig. 2, the first transition takes place at about 10 grains in the cross-section, which is consistent with the findings from [59] (‘less than 20’). Other authors expect the transition for significantly less grains, as small as 2 [60] (see Fig. 10) or more grains of up to 50 [61].

A very comprehensive model by Justinger et al. [62,63] on the scatter leads to the conclusion that 50 grains should be in the deformed volume. The deformed volume is for example the cross-section of a tensile sample or a ring element in the flange during deep drawing. If there are fewer grains in the relevant volume, the scatter will increase. The model is then based on the calculation of the Taylor factor, and it deduces the expected scatter for the process force. The earlier onset of scatter (below 50 grains in the cross-section) is not a contradiction to the noticeable reduction of the process force. The earlier onset of scatter (below 50 grains in the cross-section) is not a contradiction to the noticeable reduction of the process force.

The second transition is expected, if the characteristic size of the objects approaches the characteristic length at which the validity of the dislocation theory has its limits. This will be at feature sizes of some μm, being relevant for micro cutting, but less relevant for micro forming. According to Fig. 2, this is expected at a dimension of 1–10 μm.

4. Tribology

4.1. Scalable friction tests

From the large variety of tests for the determination of the coefficient of friction (COF), only a few were used in scaling experiments. This is obviously due to the fact that many tests demand the use of special equipment such as the Duncan–Shabel test or the draw beam simulator, which cannot be directly used for scaled experiments, but would demand a large number of scaled devices. Therefore, the high costs for the equipment prevent the application of many friction tests. Nearly all tests which are used in scaled experiments are based on the numerical identification of the COF or the friction factor μ. No comprehensive work using direct measurement of friction forces in scaled experiments was found in the literature. Only Mori et al. used a direct measurement of the COF and, gave an in-depth analysis of the results, but only two different sizes, with contact areas of 13 mm² and 75 mm², were used [64].

The ring-upsetting test, which uses the friction-dependent change of the inner diameter when upsetting a ring-like sample, is one of the most frequently used tests in scaling experiments [65–67]. The identification of the COF or the friction factor μ is mostly done by FEM simulation. Especially, Geiger and Engel et al. make alternatively use of the double cup extrusion test [68–70] for scaled experiments.

For sheet metal forming, experiments conducted with scaled deep drawing dies are used for the determination of the COF. In the reported work, either the COF is determined from the maximum force in deep drawing [71], or it is identified by a numerical identification based on an analytical model for a stripe drawing test with twofold deflection [72,73].

4.2. Lubricated friction

4.2.1. Sheet metal forming

Generally, the COF appears to increase with decreasing size. According to Fig. 11, the COF decreases with increasing contact pressure up to a contact pressure of 5 MPa, above which the COF is almost constant. For a scaling factor of 100, the COF increases by a factor of 2.4 (at a contact pressure of 5 MPa), which probably can be explained by the lubricant pocket model (see below). Due to the importance of the friction in sheet forming, the FEM simulation can be significantly enhanced when using size-dependent COF [74]. Especially if the non-uniform pressure distribution is taken into account, very good results are derived for different dimensions of the workpiece [75].

The same order of magnitude and drop of the COF is measured by the numerical identification from the maximum drawing force [71]. In contrast to the results shown in Fig. 11, only one COF, independent from the contact pressure is determined by this method. However, the increase of the COF from 0.05 to 0.13 for punch diameters of 50 mm and 1 mm, respectively, correlated well with the other experiments.

Using the size-dependent COF, the change in the limiting drawing ratio (LDR) in scaled experiments was interpreted [76]. It was seen that the COF is one of the decisive, but not the only factor for the changes in drawability.

4.2.2. Bulk metal forming

One of the first investigations of scaling effects in bulk metal forming, which showed a considerable influence on the friction behaviour, was done by Pawelski et al. [77]. A reduction in the coefficient of friction with increasing size was found [3]. The trends obtained in lubricated friction experiments in bulk metal forming are the same as that in lubricated sheet metal forming, i.e., the coefficient of friction [58] or the friction factor [68] increase with decreasing size. All observations are explained by the lubricant pocket model, while a model by Engel et al. also accounts for the surface texture [78].

Scaled plane-strain compression tests were used to evaluate the size effect on the COF in bulk metal forming with the aim of application on flat rolling [58]. Lubrication with oil was used for
the detection of size effects, while tests using a combination of PTFE foil and boron-nitride gave standard results with a COF of 0.1. As shown in Fig. 12, the COF increases by a factor of 3.8, when decreasing the size from 4 mm to 0.5 mm. Also rolling experiments showed a similar trend, but due to some severe restrictions in the scaling possibilities the observed effect in rolling was much less pronounced [58].

The double cup extrusion test is applied for the determination of the friction factor in scaled experiments, where the difference in sample size was only 4 [68] or 8 [79, 80]. Nevertheless, a significant increase in the friction factor from 0.01 to 0.05 was detected, which is equivalent to an influence strength (Eq. (3.2)) of 1.1. The experiments were done using constant deformation rate instead of constant sliding speed, but it was shown in [79] that the influence of the sliding velocity is rather small in the range of the applied values.

Also, in upsetting tests of AA7075 a strong size effect was observed. Scaled experiments, with MoS 2-grease as lubricant, showed an increase in the coefficient of friction from 0.03 to 0.09 when the diameter of the samples is decreased from 6 mm to 1 mm [81].

4.2.3. Lubricant pocket model

The lubricant pocket model is the only one available model for the explanation of size effects in lubricated friction. Pawelski et al. [77] were the first to offer a suggestion to explain experimental data using the basic feature of this theory, but without offering a quantitative description of this model. The basic feature of this model is the fact that lubricant is entrapped in pockets between the surface of the workpiece and the tool. If these pockets are fully sealed by a surrounding uninterrupted direct contact of the two surfaces, the lubricant cannot escape and a pressure can be built up, which quickly achieves nearly the value of the local contact pressure between the die and workpiece [82]. This lubricant bears a part of the load, to which the workpiece is exposed by the tool. In contrast to the load-bearing direct contact between tool and workpiece, there is essentially no shear stress transferred by the indirect load by the lubricant. At the free border of the macroscopic contact area, the lubricant can pour out of the lubricant pockets, as these have free surface parts, i.e., they are not fully sealed off. Therefore, the lubricant in open pockets will not bear any load, exhibiting the asperities of the workpiece to a higher pressure, which will flatten the asperities, increase the real contact area, i.e., the integral sum of all contact increments between the surface asperities of the workpiece and the tool, and finally increase the friction factor. A qualitative description is given in [10], and a quantitative explanation was given by Engel [83, 84], starting from the Wanheim-Bay model. Due to the complex nature of the changes of the real contact area, only an iterative numerical solution of the model is possible. Based on the consideration of open and closed lubricant pockets, the sheet surface was improved for enhanced deep drawing behaviour [85].

There are some possibilities to validate the model. One is by the type of lubricant. If it is true that the size effect is due to the loss of lubricant in the open pockets at the boundary, the size effect should not be visible with solid lubricant. As can be seen from Fig. 13, this is indeed the case.

A very comprehensive work for the validation of the model is given by Tiesler [79]. If it is true that the open pockets at the border of the contact area are only dependent on the contact pressure and the surface topology, the relative amount should change not only with a correct scaling of the samples, but also with a simple reduction in height, if double cup extrusion is considered. It was shown that there was also a drastic increase in the friction factor, if only the height of the samples was reduced [79]. It seems also plausible that the surface will be flattened stronger, if there is a larger effective contact pressure, i.e., in the area where open lubricant pockets are dominant. Indeed, such a dependence of the flattening and other indicators for the validity of the model have been shown by Tiesler [79].

The lubricant pocket model describes a micro geometry size effect. One could argue that the size effect would disappear, if the surface roughness is scaled down equivalent to the sample size, which would be possible, at least to a certain extent. From the findings of Bay et al. (see for example, [82, 86]), it is expected not to be the case: the entrapped lubricant is squeezed out during the sliding action, reducing the COF. If the surface structure is scaled down at the same ratio as the sample size, a shape balance effect is likely to occur: the surface area is reduced by r 2, while the volume of the lubrication pockets is reduced by r 3. Thus, there will be less lubricant in the micro than in the macro part, leading to worse lubrication and again to an increase of the COF. This effect is known from the lubricated sliding behaviour of polished surfaces.

4.3. Dry friction

Size effects in the friction behaviour for dry friction were only investigated for bulk metal forming. The results are at the moment not unambiguous, as some authors find that there are no size effects [65, 64], while others state that the friction is either increasing [87] or decreasing [67] when decreasing the sample size. A very detailed analysis of the friction was done [64] to explain the effects which were found in scaled forward extrusion experiments using brass (Cu:Zn 70:30) by [88, 89]. An experimental investigation of frictional behaviour in dry micro extrusion of pins with diameters ranging from 0.57 mm to 1.33 mm was conducted in [89]. Based on the comparison of the experimentally measured ram force or the extruded pin length with FE-simulation or analytical models, it was found that the COF decreased when the size of extruded pins decreased (Fig. 14), except the case of numerical identification of the COF from the pin length. A direct measurement of the COF (unfortunately, only two values for each
varied parameter were used) using a flat ring on disk-experiment showed that there is no statistically significant influence of the grain size (32 μm and 211 μm), contact pressure (22 MPa and 250 MPa) or contact area (13 mm² and 75 mm²) [64]. The differences which are shown in Fig. 14 were explained to be due to the fact that for the two small samples there are less than 5 grains across the diameter of the extruded pins. This results in an individual behaviour of the particular pins which cannot be described with the models used in numerical identification, as these models assume a continuum material [64].

A numerical identification of the COF from scaled dry ring compression tests for brass (Cu:Zn 85:15; inner diameter from 0.5 mm to 4.25 mm) reveals an increase in friction with decreasing size at least for coarse grained material [66], see Fig. 15. It was explained by a shape sum effect (see Table 1) from the importance of the real contact area for the COF. It was argued that the soft grains at the edge of the ring compression samples show a faster flattening than the harder grains in the middle of the contact area. As a result of this, the real contact area is larger for the soft edge grains. Additionally, the COF is proportional to the real contact area. Decreasing the diameter d of the ring-shaped sample increases the relative amount of edge grains according to 1/d, which results in an increase in the relative real contact area, and therefore an increase in friction [87].

Ring compression tests using magnesium alloy AZ31 at elevated temperatures [350–450 °C] show a decreasing friction factor with decreasing size [67]. The effect was less pronounced at the higher temperatures. Unfortunately, until now there is no satisfactory explanation for this effect. A comparison of lubricated and dry friction in flat rolling was done by van Putten et al. [58]. They show the known effect of increasing COF in lubricated friction, while in dry friction the COF is independent of the size.

Finally it seems that there might be different explanations for the results, but it appears to be very doubtful that a general model explaining differences for the COF in dry friction can be found. Therefore, it can be concluded that a general size effect, as described in lubricated friction, does not exist for dry friction.

5. Formability

5.1. Sheet formability in tension

Through tensile and bending tests it is found that: for \( T/D > 1 \) (\( T \): thickness, \( D \): average grain diameter), the yield strength and tensile strength decrease with the decrease in \( T/D \) ratio; for \( T/D < 1 \), the yield strength and tensile strength increase with the decrease in \( T/D \) ratio. The lower the \( T/D \) ratio, the worse is the formability [30].

Scaled tensile tests were performed to investigate the size effects on flow curves and fracture strain for Cu foils [90], Al 99.0–99.5% [29] and for CuZn36 [91]. The experimental results show a decrease in the yield strength and the maximal true strain with a decrease of specimen thickness, see Fig. 16. Numerical results in biaxial stretching of mild steel, annealed aluminium and annealed 70/30 brass show that limiting strains decreased as the ratio of thickness/grain size decreased [92]. Simulations of uniaxial tension and three-point bending tests involved a study of different orientations of grains and showed that a decrease in sheet thickness leads to a decrease in formability [93]. Tensile tests of metal foils (SE-Cu 58) show that strain to fracture decreases with foil thickness as a result of increasing inhomogeneity of the microstructure with decreasing the ratio of the foil thickness to grain size [94].

5.2. Forming in upsetting

The effects of specimen size and loading rate on the flow stress and failure behaviour of workpiece under compressive loads were investigated. The influence of temperature changes at different strain rates within scaled experiments was discussed. It was found out that for one Al and Ti alloy, the failure strain depends on both a geometrical and process variables [37,95], see Fig. 17.
5.3. Forming limit diagram (FLD)

It has been found experimentally that the level of FLD increases with sheet thickness $s_0$ and strain hardening exponent $n$. Keller and Brazier [96] have approximated this effect by

$$FLD_0 = n(1 + 0.72s_0) \quad \text{for} \quad n \leq 0.2$$

$$FLD_0 = 0.2(1 + 0.72s_0)$$

The results are plotted in Fig. 18. As shown in Fig. 19, Hašek and Lange [97] experimentally confirmed the impact of sheet thickness on the FLD for mild steel.

A new flexible micro sheet metal forming process – micro incremental forming – was investigated. The geometrically similar experiments using different sheet thicknesses also provided lower forming limits for thinner sheets [98]. FLDs obtained by bulge tests (Fig. 20) showed the decrease in formability with decreasing the sheet thickness [99]. Size effects on flow stress and the influence of grain dimension on material formability were investigated through tensile tests and formability tests with specimens in different sizes. It has been found that finer grains have a positive impact on the position of FLD [31] as demonstrated in Fig. 21.
was confirmed by other experiments, where the grain size was held constant and the sheet thickness was varied between 500 μm and 25 μm. A significant decrease in the maximum strain (at ε1 = ε2 = 0.25) as the sheet thickness decreased from 500 μm (at 25 μm) was detected [100].

Deep drawing with different specimen thickness and different ratios of punch diameter/specimen thickness was carried out. The limiting drawing ratio (LDR) decreased with increasing ratio of punch diameter/specimen thickness [101].

Using dies with different diameters, bulging tests with sheets of different materials in different thickness were performed to investigate the effect of thickness on the restoration of bulged specimens [102]. It has been ascertained that the thinner the sheet metal, the greater the effect of buckling on the formation of wrinkles.

The study of micro deep drawing sheets from Al 99.5 with thickness from 1 mm to 0.02 mm show that the LDR in micro deep drawing is significantly smaller than in macro deep drawing [76], which is not only due to the changes in friction behaviour. Lee et al. pointed out the importance of the ratio of sheet thickness to grain size. This ratio drops below 10, a significant decrease in the LDR was observed [103].

6. Forming

Forming operations cover bulk and sheet metal forming both in cold conditions and at elevated temperatures. In [8], a comprehensive description of the state-of-the-art in micro forming is given. Table 2 indicates the types of micro forming processes that have been investigated with respect to size effects. In the following sections size effects related to forming forces and stresses, processing windows and accuracy will be described. It is clear that specific experimental work will be related to specific process and material conditions. However, the present section will use selected cases to illustrate the general findings in the literature.

6.1. Forming force and stresses

A very early work on the influence of the size of the workpiece in bulk metal forming was done in backward can extrusion [104]. It was shown that the maximum forming force can be determined from

\[ F_{\text{max},2} = m \times F_{\text{max},1} \times \frac{k_f}{k_f^1} \times \lambda \]  

where \( F_{\text{max}} \) is the maximum force, \( k_f \) is the flow stress, and \( \lambda \) is the length scale factor. The correction factor \( m \) was determined to lie between 0.6 and 1.1 and is considered to be a quantitative measure for the sum of different size effects. One of these effects was based on the surface to volume effect (shape balance in Table 1), yielding stronger heating of the material by the deformation work in case of the larger samples [104]. Grain size effects play obviously no role, as the sample size was above 20 mm.

6.1.1. Bulk

A general observation in micro cold forming operations in closed dies is that a decrease in part dimensions will result in an increase in punch pressure defined as punch force divided by cross-section area of punch [8]. This is explained by the increase in friction, and this has been confirmed by both experimental and numerical investigations. As previously stated, the effect of grain size relative to dimension also plays an important role. Extrusion experiments with different die diameters were performed to investigate the friction behaviour. Three different coated dies were used to reduce the friction, and consequently the extrusion force [88]. An implementation of processes at elevated temperatures decreased the necessary forming forces in the example case reported in [105]. Micro embossing with laser assistance has also been carried out. The results show the potential advantages in reducing the forming force and the risk of tool fracture, when a high power laser was used [106].

6.1.2. Sheet

Two different size effects were observed in the analysis of the micro deep drawing process detailed in [107]. The maximum relative punch forces were found to be independent of the scaling factor (which describes the ratio of the actual punch diameter to a reference punch diameter of 8 mm), but were dependent on the grain size to sheet thickness ratio. The maximum punch forces of the bigger cups decrease with increasing velocity, while the punch forces for the smaller cups do not. A thermally coupled FE-simulation show that this could be partially related to the thermal influence caused by heat generated from plastic dissipation and friction, in combination with the differences of the surface to volume ratio for the different scaling factors. Investigations in [108] show that the design of micro deep-drawing processes (e.g., force) is subject to a heavier influence of production-determined deviations concerning the design contours of the tool than in the case of conventional, large-sized parts. Therefore, these production-determined deviations from the ideal geometry need to be taken into account in the process design.

Investigations on the bending process were carried out in scaled experiments. The influence of grain size and orientation on the bending force and strain distribution was investigated. It was pointed out that it is impossible to develop a universally applicable FEM model [109]. In [57] size effects on flow curve and bending force were investigated. These effects were explained in terms of the change in the grain size/specimen size ratio.

The effect of grain size and orientation of the specimen on the process force and strain distribution within micro blanking and bending tests was investigated. It was concluded that it is impossible to develop a universally applicable FEM model although significant work was subsequently undertaken on this subject [110].

6.1.3. Scatter of forces

Another remarkable size effect is the general increase in scatter of forming forces when dimensions are decreased [10], [111] reports on a decrease in the observed scatter of forces when using
ultrafine-grained copper compared to coarse grained material in a backward extrusion operation. A numerical mesoscopic model was developed, with which a size-dependent simulation can be realised [112]. Experimentally it was observed that increasing scatter of the grain size results in increasing scatter of the forming force [113].

6.2. Processing windows

6.2.1. Extrusion

In [114] a full backward extrusion process was investigated experimentally using a full factorial design of experiments in a high conductivity copper (Cu-ETP). Five main parameters were investigated: temperature, grain size, punch velocity, lubrication and pin diameter (see Table 3 for details). Among these factors, the temperature and the pin diameter were found to be the most significant along side with the lubrication. In particular, the interaction between temperature and pin diameter was investigated with fine grain size, no lubrication and punch velocity 3 mm/min. Experiments were performed with a max force of 200 N. This second level interaction was the only one found to be significant at a 95% confidence level. Fig. 22 illustrates the obtained aspect ratios of a 2.0 mm and a 0.5 mm pin diameter at 20 °C and 200 °C, respectively. In [115] a comparison of processing windows between two different material types is presented for a combined forward extrusion and embossing process. A 1.5 mm billet is extruded and embossed on the top surface of the component. The component was successfully manufactured in a silver alloy using a two-step forming procedure in cold conditions, the thinning of the cup walls became more pronounced for smaller cups, although the flow stress curves of all annealed materials are nearly in the same range.

Table 3

<table>
<thead>
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<th>Parameters investigated in [114]</th>
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<tbody>
<tr>
<td>Lower limit</td>
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<tr>
<td>Temperature</td>
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<tr>
<td>Grain size</td>
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<tr>
<td>Punch velocity</td>
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<td>Lubrication</td>
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<td>Pin diameter</td>
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Micro coining of thin sheet metal in different thicknesses was experimentally investigated, using a FE-analysis [120]. The distribution of non-dimensional forming height in coining with micro cavities was found to be different for different micro cavity diameters. This effect was explained by relative sliding and, it was shown that the law of similarity cannot be applied to this case [121].

6.2.2. Deep drawing

In [116] experiments at various punch speeds ranging from 0.01 mm/s to 100 mm/s were performed on CuZn37 foils in as-delivered and annealed conditions (3 h/600 °C) with thicknesses ranging from 300 μm down to 40 μm. The blank diameters were scaled corresponding to the thickness. Wall thickness distributions were measured on the produced cups using a microscope. The experiments show that the punch velocity has only a small effect on the cup geometry. The cup geometry seems to be more affected by the microstructure. Under annealed and coarse-grained conditions, the thinning of the cup walls became more pronounced for smaller cups, although the flow stress curves of all annealed materials are nearly in the same range.

Micro deep drawing with different punch diameters was experimentally and numerically investigated [117]. The influences of friction coefficient, deviations of transverse anisotropy and deviation of tool geometry on the process were discussed. Scaled deep drawing was carried out. The punch force acquired in FEM-simulation agreed closely with the experimental results. The velocity of the punch showed effect on the punch force only by the punch diameter of 8 mm [118]. Size effects in sheet drawing were determined by means of multi-grain model based on crystal plasticity theories, which accounts for the interaction among the individual grains [119].

6.2.3. Upsetting and coining

Upsetting and coining of thin sheet metal in different thicknesses were investigated through tensile tests, bending and blanking processes. The effect of grain size was analysed [29]. Bending tests were carried out using specimens with different thicknesses. The effects of the ratio thickness/grain size on the tensile strength, microhardness and spring-back were analysed [124].

Fig. 22. Full backward extrusion. Effect on aspect ratio of pin diameter and temperature (by courtesy of [114]).
Though scaled tensile test, air bending and punching, the size effects were investigated [125]. The causes for the size effects occurring in tensile tests were analysed and transferred to the air bending and punching [126]. A model for FE-simulation of micro bending process was described. The influence of punch radius, die radius, specimen thickness, etc., on the final parts geometry were investigated [127]. The spring-back behaviour of brass was investigated by three-point bending with different thicknesses. The correlation between spring-back and the thickness/grain size ratio was discussed [128]. The effects of grain size and specimen size on final bending angle within the V-bending were investigated. The larger the grains size, the lower the spring-back [129].

6.3.2. Surface appearance
Aiming at development of a similarity law for the spinning process, the correlations between surface quality and contact pressure, sliding velocity and strain were investigated [130]. In [61] an attempt to model the surface evolution due to contact loading was presented. With the help of the proposed model, the influence of grain size and orientation as well as strain rate have been verified and quantified.

6.3.3. Shape accuracy
Shape accuracy is an important quality parameter in micro forming processes since net shape processes are the ultimate goal also in micro forming.

A very impressive example of the influence of a size effect on the shape accuracy was shown in [64]. The occurrence of curved samples was assumed to be an effect of inhomogeneous deformation in the coarse-grained samples, while the fine-grained ones did not show the curvature even in multiple repeated experiments. It was reported in [89] that using the same smallest extrusion die which reduces the diameter from 0.76 mm to 0.57 mm (marked with '0.76:0.57 mm'), specimens with 32 μm grain size resulted in all straight pins, while 60% of pins with an original grain size of 211 μm showed an uncontrolled curvature in the final extruded pins. These results indicate that the size, orientation, and distributions of grains play an important part in the extrusion process. A more detailed analysis of local hardness and microstructure of deformed pins to illustrate the size effect can be found in [131]. The importance of the local flow behaviour of individual grains for the shape accuracy is shown by Geißdoehr et al., who did backward extrusion in the micro range using a partly transparent tool. The homogeneity of material flow decreased with increasing ratios of grain size to extruded wall thickness [132,133].

6.3.4. Downscaled equipment
In the pursuit of achieving the desired accuracy, efforts have been made to downscale the manufacturing equipment in order to pursue a higher absolute precision. The main reasons are the decrease in heat deformation of machine tools with the decrease in their sizes, decrease in vibration amplitudes and decrease in space and energy consumption [134].

A micro superplastic backward extrusion machine was developed, with which microgear shafts of 10–50 μm were fabricated [135].

A laser-assisted micro forming setup was developed, on which the semi-hot embossing experiments were carried out. The risk of a fracture of the tool is lower and the quality of specimen is better [136].

In [137] and [138] a modular approach to the realisation of a high precision, flexible press for micro forming is described.

7. Cutting
7.1. General
Generally, in literature the term size effect in metal cutting is understood as the non-linear increase of the specific cutting energy with decreasing the undeformed chip thickness. Backer et al. [139] were among the first to determine the energy consumed in deforming a unit volume of a ductile material (SAE 1112 steel), and develop a relationship between the shear energy per cubic volume and the specimen size. They showed the decreasing trend in shear energy per unit volume for three major manufacturing processes: grinding, micromilling, and turning (see Fig. 24). It is to be noted that after over four decades, Taniguchi [140] confirmed this relationship through his extensive research showing the size effects observed in a range of processes including tensile test, the results are also plotted in Fig. 24. Shaw [141], in a recent analysis of size effects revisited his earlier explanation and describes the origin of size effects as resulting from a short-range inhomogeneities present in all commercial engineering metals.

7.2. Orthogonal cutting
7.2.1. Early work on experimental flow fields and strain-hardening models
Palmer and Oxley [142] showed the flow around the rounded cutting edge using cine filming techniques for chip formation at a low cutting speed. They showed the existence of a shear zone and developed a slip-line model for chip formation and the material flow around this rounded cutting edge by considering the strain-hardening property of the work material. Their model and the experimental observations correlated better compared with...
Fig. 25. Experimental flow field obtained using cine filming method for material flow around the rounded cutting edge (from [142]).

previous rigid-plastic shear plane models. An experimentally observed flow field is shown in Fig. 25.

Based on his earlier work on the use of a centered fan slip-line model for machining with a restricted contact tool [143], Johnson developed an admissible slip-line field for cutting with a double edge tool representing the rounded cutting edge. An interesting feature of this early work is that Johnson [144] was able to show a range of solutions for the plastic flow of the work material along the machined surface at varying velocities. Contemporary experimental work by Nakayama et al. [145] shows the ‘microchip’ formation at the asperity on the tool flank resulting in a plastically deformed, interrupted machined surface in cutting of a soft material with a hard tool. Larsen-Basse and Oxley [146] subsequently showed that the size effects are a consequence of material strengthening due to the increase of strain rate in the primary deformation zone when the undeformed chip thickness decreases. In a pioneering analytical work using plane-strain slip-line models and the associated hodographs (velocity diagrams) for the stress and velocity fields, Challen and Oxley [147] from single and double edge chords representing the rounded cutting edge show the existence of three specific regimes: (a) rubbing, (b) wear, and (c) cutting. This work shows an analytical formulation with the use of similarity mechanics involving a non-dimensionalized parameter of the ratio of undeformed chip thickness to tool edge radius. Kopalinsky and Oxley [148] show the size effect as resulting from the strain rate and temperature-dependent flow stress properties of the work material. In a further work, Kopalinsky et al. [149] show the generation of tensile stresses on the machined surface due to the severe plastic deformation.

7.2.2. Ploughing effects and force models

An early work by Masuko [150] reports the effects of cutting edge radius through a cutting force analysis. Albrecht [151] developed a ploughing force model to explain the size effect. By dividing the tool–chip–work contact region of the cutting tool into four sections, he developed a force relationship for the cutting process involving a rounded cutting edge tool (see Fig. 26). He showed an experimental method to separate the ploughing force from the cutting force. He also correlated the ploughing force with the chip curl and the residual stresses generated in machining.

Armarego and Brown [152], using their experimental results from machining of aluminium alloy 50-5T in a soft 1022 HSS rectangular tool show that specific cutting energy reduces as the undeformed chip thickness reduces, and after reaching a certain value, it increases exponentially with further reduction in undeformed chip thickness, for 1022 steel. Shaw argues in the discussion of this paper that circular and rectangular tools might differ in the way the force, and hence the specific cutting energy, is generated in machining, and that the formation of a small built-up edge may have caused this variation from the conventionally observed trends of continuous increase of specific cutting energy when the undeformed chip thickness reduces.

Nakayama and Tamura [145] developed a force-based analysis to describe the size effects in cutting at small depths, and feeds and demonstrated it experimentally by showing that the size effect is attributed to the subsurface plastic work, implying the surface integrity in terms of subsurface metallurgical and microstructural changes. Khaet and Vasilyuk [153], through a series of experimental work with a range of work and tool materials, showed the optimum value of the ratio of undeformed chip thickness and tool edge radius to provide the maximum tool edge strength.

Abdelmoneim and Scrutton [154] showed the existence of plastic recovery behind the cutting tool in machining with a negative rake tool and attributed this to the intending action of the cutting tool edge. In their subsequent work, Abdelmoneim and Scrutton [155] developed a theory for cutting with a rounded cutting edge tool by assuming the existence of a stable built-up edge ahead of the cutting tool, and show the dependence of the specific cutting pressure on the ratio of undeformed chip thickness to edge radius. Taminiau and Daoutzenberg [156], through a series of analytical and experimental work verified the model by Abdelmoneim and Scrutton [155] in high precision cutting by plotting the specific cutting and thrust force against the ratio of undeformed chip thickness and tool edge radius.

Lucca and Seo [157] conducted an experimental study of orthogonal cutting of Al6061-T6 alloy to examine the dissipation of mechanical energy in cutting at small depths of cut, and show the transition from cutting to ploughing and report the significant effects of tool edge radius in cutting. In a subsequent work [158], they show the significant effect of cutting edge geometry on the cutting force components and the plastically deformed machined layer.

More recently, Arsecularatne [159] used Oxley’s predictive machining theory [160] to investigate the ploughing force, and separated the cutting force from the ploughing force, and used it in the calculation of tool–chip interface stress distributions. Dinesh shows that if the flow stress of a material is dependent on a strain gradient parameter, size effects should be expected when machining this material, i.e., increasing specific cutting force with decreasing undeformed chip thickness, which is also related to indentation size effects [161]. A further cutting model accounting for the edge radius size effect is given by Bissacco et al. [162].

7.2.3. Chip formation

Clos et al. [163] experimentally investigated the strain localisation in cutting as an adiabatic shear banding mechanism. In orthogonal cutting experiments, a change in the chip forming process from continuous to segmented chip formation with increasing undeformed chip thickness was found [164].

A changing chip formation was also found when scaling the undeformed section of cut in turning processes with large corner radii. The changed chip formation mechanisms were accounted for the higher specific cutting forces. A model for the description of chip formation is currently under development [165].
7.2.4. Cutting edge radius

The cutting force and feed force in hard turning by different ratios of \( r_d/h \) (cutting edge radius/undeformed chip thickness) were experimentally investigated [166]. In addition, scaling effects of the process parameters, e.g., undeformed chip thickness \( h \) and cutting edge radius \( r_d \) on the chip formation, cutting force and surface quality in hard turning was investigated [167]. It was found out that cutting force and feed force rise rapidly with increasing cutting edge radius. In further investigations, a scaling of the cutting edge radius and the undeformed chip thickness in orthogonal machining was carried out. Chip formation, degree of segmentation and shear band width are affected by the scaling of the cutting edge radius [168]. The influence of a scaling of cutting edge radius or chamfer and depth of cut on the burr formation in orthogonal machining was investigated by [169]. Through experiments and a FE-simulation, non-linear influence of the size of a cutting edge chamfer on the temperature, the mean stress in the burr shear zone and on the size of the hydrostatic bowl were found.

7.2.5. Analytical and numerical models and experimental validation

(a) Analytical models and experimental validation

There has been significant effort to model the micromachining process using various analytical modelling methods including molecular dynamic modelling, multi-scale modelling and mechanistic modelling. A good summary of these modelling methods are given in a recent CIRP keynote paper by Dornfeld et al. in 2006 [170].

Manjunathaiah and Endres [171] developed a new model for orthogonal machining with an edge radius tool. This model consisted of a geometry model and a force model. They show that the increase in specific cutting energy with edge radius is substantially due to the energy expended in shearing the chip due to the apparent more negative effective rake angle. They also attribute this increase, and hence the size effect, to increases in strain and strain rate. This work was extended to an extensive experimental study of orthogonal machining of zinc involving a range of edge radius tools [172]. They tested the two traditionally known methods for extracting the ploughing force: extrapolation method, and dwell method, and show that neither of these two methods yields to a consistent material behaviour.

Joshi and Melkote [173] modelled the primary deformation zone through a simple parallel-sided configuration using the strain gradient plasticity theory, and explained the occurrence of size effects in machining. By extending this work to include the secondary shear zone, in a subsequent work, Liu and Melkote [174] compared the variation of maximum temperature (see Fig. 27), and compared the specific cutting energy developed with strain gradient model and without strain gradient model (see Fig. 28). This paper shows two material strengthening factors: (i) the decrease in the secondary deformation zone cutting temperature, and (ii) strain gradient strengthening. This work also shows the relative contributions of these two factors to the increase in specific cutting energy when the undeformed chip thickness is reduced. Also shown is an analysis of the finite element orthogonal cutting model which performs simulations on Aluminium 5083-H116, which has a small strain rate hardening exponent, thus minimizing strain rate effects.

(b) Slip-line models and experimental validation

Early work on the use of slip-line models for orthogonal cutting at small depth of cut and for the polishing processes shows the material flow around the rounded cutting edge using single and double edge chords [147] to represent a range of frictional conditions and tool edge radius. Account is also taken of lubrication conditions. Based on their earlier slip-line model for negative rake angle cutting [175], Abebe and Appl [176] developed a new model for the ploughing abrasive process using "effective planes" to represent the three-dimensional machining process through slip-line and upper bound models.

More recent work by Fang [177] involves a rounded cutting edge and multiple cutting edge chords, and this work is based on the extended application of the universal slip-line model developed for machining with a restricted contact tool [178]. More recently, Wang and Jawahir [179,180] show an admissible slip-line model with the corresponding hodograph for machining with a restricted contact grooved tool having a rounded cutting edge represented by double cutting edge chords, BS and SN – see Fig. 29.

The non-linear system of slip-line model is based on the five slip-line angles \( \theta_1, \theta_2, \theta_3, \theta_4, \theta_5 \) and their five equations:

\[
\begin{align*}
\frac{F_1}{k_{t1}w} &= F_{A_{1}A_{1}} + F_{A_{1}A_{0}} + F_{A_{0}A_{0}} + F_{A_{0}C_{1}} + F_{C_{0}D_{1}} + F_{D_{1}B_{1}} + F_{B_{1}B_{1}} \\
\frac{F_2}{k_{t1}w} &= M_{1} + F_{A_{1}A_{0}} + F_{A_{0}A_{0}} + F_{A_{0}C_{1}} + F_{C_{0}D_{1}} + F_{D_{1}B_{1}} + F_{B_{1}B_{1}} \\
\frac{F_3}{k_{t1}w} &= h_{1}^{2} - (X_{f_{1}f_{2}} - Y_{f_{1}f_{2}})^{2} + (X_{f_{1}f_{2}} - Y_{f_{1}f_{2}})^{2} = 0 \\
\frac{F_4}{k_{t1}w} &= h_{1}^{2} - (X_{f_{1}f_{2}} - Y_{f_{1}f_{2}})^{2} + (X_{f_{1}f_{2}} - Y_{f_{1}f_{2}})^{2} = 0 \\
\frac{F_5}{k_{t1}w} &= (R_{0} + \frac{f_{2}}{2}) \sin(g_{f_{2}} + \eta_{g}) - \frac{GW}{2} = 0
\end{align*}
\]

The non-dimensionalized (similarity mechanics-based) resultant force \( F \) developed is shown as

\[
\frac{F}{k_{t1}w} = \frac{F_{A_{1}A_{1}}}{k_{t1}w} + \frac{F_{A_{1}A_{0}}}{k_{t1}w} + \frac{F_{A_{0}A_{0}}}{k_{t1}w} + \frac{F_{A_{0}C_{1}}}{k_{t1}w} + \frac{F_{C_{0}D_{1}}}{k_{t1}w} + \frac{F_{D_{1}B_{1}}}{k_{t1}w} + \frac{F_{B_{1}B_{1}}}{k_{t1}w}
\]

The ploughing force \( P \) was derived as

\[
\frac{P}{k_{t1}w} = \frac{F_{B_{1}B_{1}}}{k_{t1}w} + \frac{F_{B_{1}M_{1}}}{k_{t1}w} + \frac{F_{M_{0}M_{1}}}{k_{t1}w} + \frac{F_{M_{1}N}}{k_{t1}w} + \frac{F_{M_{1}N}}{k_{t1}w}
\]

where \( k \) is the shear flow stress and \( w \) is the width of cut. This model predicts cutting forces, chip thickness, chip up-curl radius, temperatures and flow stresses at the primary shear zone and at the tool–chip interface, etc. Predictive modelling of size effects using the above slip-line model for machining with a rounded cutting edge tool shows the effects of cutting edge radius and

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Fig. 27. Variation of maximum temperature in the primary and secondary shear zones at 200 m/min cutting speed (PSZ: primary shear zone; SSZ: secondary shear zone) ([from 174]).

Fig. 28. Variation of specific cutting energy with uncut chip thickness at 240 m/min ([from 174]).
During the past decade, there has been a surge in numerical modelling of orthogonal cutting to predict the various machining parameters including the size effects in finish machining at small cutting depths (undeformed chip thickness). A finite element method was developed to predict the temperature and the stress distribution in micro machining [182]. The influence of the cutting edge radius was considered in this model and the results confirm that the cutting edge radius is one of the major causes of the size effects. Özel and Altan [183] show the effect of edge radius on forces and stresses developed in machining. Yen et al. [184] in a follow-up work, used a range of tool edge configurations including chamfer and hone radius conditions and simulated the material flow by calculating the stresses, strains and temperatures. They showed the ploughing effect and related the edge radius with the resulting force, temperature and stress conditions.

Using a thermal elastic-viscoplastic finite element model, Êe et al. [185] predicted the residual stresses induced by machining when using edge radius tools. Simoneau et al. [186,187], Liu and Melkote [188] studied the size effects influenced by the tool edge radius in microcutting of A15083-H116 alloy using the ABAQUS finite element software with strain gradient plasticity formulation. Weber et al. [189] used a thermo-mechanically coupled finite element method to study the problem of size effects in normalized steel AISI 1045 and annealed AISI 02 using the ABAQUS/Explicit having a provision for modelling the viscoplastic behaviour of the work materials with a range of dimensionless similarity mechanics parameters representing the material law in the model. They show the effects of cutting speed and the cutting edge radius on size effects.

Size effects in metal cutting concerning the cutting force and roughness were experimentally investigated. A FEM-simulation including the use of similarity mechanics to establish the parametric influence of various factors was attempted [190]. Hochrainer et al. [191] carried out a 2D FE-simulation of orthogonal cutting using similarity mechanics approach, and investigated the correlation between normalized specific cutting force and similarity number as well as relative sharpness. Size effects influenced by the specific cutting force are described in terms of strain hardening, heat distribution in front of the cutting tool and by non-linear increase in the plastically deformed surface layer. Machining with multiple passes requires the effect of previous pass in the newly generated surface layer which influence the specific cutting force and the depth of plastic deformation [192]. Also, experimental and numerical investigations to determine the influence of the friction coefficient on the specific cutting force were carried out. A linear dependence of the specific cutting force on the friction coefficient was shown, which leads to an intensification of the size effect for higher friction components [193].

Outeiro [194] measured experimentally and established the effect of cutting edge radius on the thermo-mechanical conditions developed in metal cutting. In particular, he found that increasing the ratio of undeformed chip thickness to cutting edge radius (h/r_s) leads to an increase in the temperature developed in the cutting zone, and a greater part of this heat is conducted into the workpiece and the tool, this resulting in high temperatures and thermally affected layers being produced on the machined surface. This usually induces higher residual stresses on the machines surface, or causes a phase change in the material [195]. Wanigarathne et al. [196] developed a finite element method for studying the effects of cutting temperatures and the cooling effects in finish machining of AISI 1045 steel with multi-layer coated tools having a rounded cutting edge under conditions producing size effects. They extended the Johnson–Cook model to incorporate the changes studied.

\[
\sigma = (A + B\varepsilon'\varepsilon^*\varepsilon^*) \times \left(1 + C\ln\left(\frac{\varepsilon'\varepsilon^*}{\varepsilon_0}\right) + D\varepsilon^*\varepsilon^* + E\varepsilon^*\varepsilon^*\cdot e^{-100\sigma/\varepsilon}\right)(1 - T^{\beta})
\]  

(7.4)

where A, B, C are the material constants, \(\varepsilon\) the strain and \(T\) is the temperature.

They showed the effects of cutting speed, coating thickness, coating thermal conductivity, cutting edge radius, tool–chip interface friction, etc., on the resulting machining performance. Fig. 30 shows the simulated results, and the temperature fields developed are correlated with the higher residual stresses and the size effects produced.

(d) Experimental findings

Subbiah [197] attributes the size effect to a component of the cutting force, which remains constant with decreasing undeformed chip thickness. By machining with very large rake angles (up to 70°) the shear influences in the chip could be minimized and the constant cutting force component could be isolated. Chip formation with these high rake angles occurs mainly by ductile fracture or ductile tearing ahead of the cutting edge. The value of the constant force component is in the range of the force of ductile fracture and crack formation. This work is consistent with the
theory of Atkins [198] which attributes the size effect to the energy which is needed for the formation of a new surface by ductile fracture. This energy is independent from the cutting force, and therefore, responsible for the size effect. The increasing of specific cutting force with decreasing of cross-section of undeformed chip was observed and analysed [199].

7.3. Turning operations

Shawky and Elbestawi [200] developed a mechanistic cutting force model for turning which included the effects of ploughing force. The comprehensive CIRP collaborative work on modelling of machining operations presents the shortcomings of all current models in accurately predicting the edge effects in turning [201]. Redetzky et al. [202] presented a generic predictive model for chip flow and cutting forces which combined a geometric model and a force model. This model included the cutting edge effect and considered the size effects.

Significant effects that could be attributed indirectly to the size effect phenomenon can be seen in some complex machining operations such as contour turning. In an experimental study of contour turning of two aluminium alloys (6061-B and 2011-T3), Balaji and Jawahir [203] observed that there are drastic changes in machining performance measures such as cutting forces, chip-flow and chip formation, and surface roughness induced by the continuously varying geometry due to the complex geometry of the contour shape. Balaji and Jawahir [203] tested two cutting tools (a flat-faced polycrystalline diamond tool (PCD) and a grooved CVD diamond-coated carbide tool (DCC)). In contour turning, there are continuous changes in the effective depth of cut and effective feed along the contour, which leads to drastic changes in the effective mechanics of the machining operation. The significant changes in effective depth of cut and feed also lead to continuously varying size effect conditions along the contour. In this particular study, the flat-faced PCD tool was relatively up-sharp with no significant home to its cutting edge, whereas the diamond-coated grooved tool (DCG) has an edge-hone to provide edge strength and stability to the cutting edge. The changing effective geometry of the cutting conditions and the cutting edge impose size effects in the surfaces generated. Surface roughness was measured at discrete locations along the contour profile for the finish machining case. An interesting observation was that the diamond-coated grooved tool largely produced a rougher surface when machining the 6061-B alloy, but ended up being far superior to the PCD tool when machining 2011-T3 alloy. The role of size effect in influencing different surface texture when machining different alloys with different tools remains an interesting area for future study of the fundamental mechanics of material removal.

More recent comprehensive analysis of the cutting edge radius effects in turning includes development of a new model for predicting the apparent area of contact in the cutting edge region [204]. A typical apparent undeformed area of cut (view on tool reference plane $P_r$) is shown in Fig. 31 for a finish turning process.

According to the position of the given point $S$ ($S = A, B, C, D, E$) on the circular cutting edge, the entire undeformed area of cut can be divided into four regions: Region 1: $ABJ$, Region 2: $BEIJ$, Region 3: $ECFI$, and Region 4: $CFD$.

The total apparent area of cut for each region is calculated by adding the apparent area of cut generated from the rounded cutting edge and the apparent area of cut generated from the rake face together. Based on the mathematical derivation, the effect of cutting edge radius on the apparent area of cut can be calculated and 3D visualized (Fig. 32). This theoretical work was followed by an experimental validation process for specific cutting energy versus the ratio of feed and cutting edge radius. An interesting similarity was observed in the pattern of apparent contact regions for all four edge radius tool groups considered. Also, an analysis of machined surface quality was done. Three patterns of machined surfaces named as acceptable, marginal and unacceptable (Fig. 33) were observed in all tests.

All machined surfaces from DLC insert are found to be acceptable. But for Diamond tool inserts, all machined surface for the ratio of feed/edge radius smaller than 0.8 are either Marginal or Unacceptable. As a result, DLC inserts generate much more acceptable machined surfaces than diamond inserts. This indicates the complex tribological interactions that are taking place in the cutting regions of these tools.

7.4. Drilling operations

Using the drills with and without web thinning, the influence of the chisel edge length on the cutting torque and feed force was...
investigated. It was found that a downsizing of the tool diameter leads to a non-linear increase of the specific feed force [205]. Furthermore, a non-linear scaling effect on the related feed force was observed in drilling tests by downsizing of drill diameter. With a proposed 3D-FE-model, the experimentally determined scaling effects are well predicted [206].

Based on the interaction between the cutting mechanisms in shearing and ploughing, a new analytical approach was developed to determine the minimum undeformed chip thickness and to predict the observed non-linear size effect in specific cutting energy (Fig. 24). Also, a 3D-FE-model was developed, and successfully validated to predict chip formation, feed force, cutting torque and temperature in drilling [207,208].

Lugscheider et al. [209] developed a FE-model to simulate the contact between a drill and specimen in micro drilling. The effect of PVD hard coatings geometry on the micro drills was discussed. The influence of a scaling of the coating thickness on microdrilling tools was investigated in [210]. The thickness of the coating influences the bending and torsional stiffness, and therefore the dynamic behaviour of the tools.

Dix et al. [211] studied the Burr formation and the temperature distribution in drilling processes with scaled tool diameter. They found the existence of size effects in the burr formation process where they showed that the burr height and the burr type do not change linearly with the tool diameter, but, the maximum temperature varies non-linearly with the tool diameter.

Paris et al. [131] developed a new cutting force model for undeformed chip thickness close to zero, called as “fractional Model” for drilling and milling, and validated it experimentally and against the traditionally known exponential function. They showed that the accuracy of this proposed new model was superior to those obtained by the exponential function.

7.5. Milling operations

Ko [212] developed a model to predict cutting forces for end milling by considering the size effect through the use of instantaneous cutting coefficients and validated it experimentally. The values of the cutting force components are determined empirically or semi-empirically. Wang and Zheng [213] proposed an analytical force model with dual shearing and ploughing mechanisms for end milling.

Other significant FEM work includes work by Vogler et al. [214] where the authors developed a cutting force model for microend milling, and by incorporating the minimum chip thickness concept, they were able to predict the effect of cutting edge radius on cutting forces. Finite element simulations were performed to calibrate the various machining parameters for micromilling force model. Their model incorporated the metallurgical microstructural features.

Bissacco et al. [215] investigated size effects on the surface generation when downsizing the tool diameter in milling processes. Size effects occur when the ratio of cutting edge radius to undeformed chip thickness becomes critical.

Weynert et al. [216,217] also studied the influence of the cutting edge radius to the process. When scaling the undeformed chip thickness subject to the tool diameter, the cutting edge radius has a major influence to the process because it cannot be scaled down in the same range as tool diameter. A small undeformed chip thickness, in combination with a big cutting edge radius, prevents a well-defined cutting of the material and leads to ploughing effects.

The influence of a downsizing of tool diameter and chip thickness on the cutting forces in micromilling was experimentally investigated by Biermann et al. [218]. Non-linear rising specific cutting forces with decreasing chip thickness were found. A geometric simulation was used to calculate the cutting forces, which matched well with the experimental results (Fig. 34).

Bissacco et al. [162] presented a theoretical model for cutting force prediction in micro milling by taking into account the size effect related to the decreasing ratio between undeformed chip thickness and cutting edge radius. This model is based on a revised implementation of the Unified Mechanics of Cutting. The comparison of measured and predicted cutting forces showed a good agreement. A recent analytical modelling work shows accurate prediction of cutting forces and their experimental validation in milling of 316L stainless steel and TiAl6V4 alloy at small undeformed chip thickness [131].

An important factor in downscaled milling processes are the tools. A decreasing tool size, related to the tool diameter, leads to an increasing deviation of the tool geometry from the tool design [219]. Another size effect which occurs is the increasing tool deflection with decreasing tool radius caused by the cubically decreasing section modulus subject to the diameter of the tools. Investigations show contour deviations of machined webs up to 30 µm when machining with a 0.4-mm tool with a length of 4 mm, while the parts machined with a 2-mm tool show almost no deviations of the desired contour [216]. This behaviour was confirmed by Uhlmann et al. [220] who examined the scaling in milling of tungsten–copper composites. A size effect was found in the tool displacement which showed a non-linear dependency on the tool diameter.

Furthermore, size effects on process force, speed, tool drift, surface roughness and natural frequencies of the tool were investigated in scaled milling of tungsten copper composites.

Fig. 33. Machined surface patterns [204].

Fig. 34. Measured (continuous line) and simulated (dotted line) cutting force progressions for different tool diameters (material: AISI P20, cutting speed: \( v_1 = 35 \text{ m/min, feed per tooth} f_z = 0.01 \times d \), depth of cut: \( a_p = 0.04 \times d \)) [218].
A non-linear behaviour of the process when using tool diameters below 1 mm was detected [221]. In further investigations, the influence of a scaling of the size of the tungsten particles and the percentage of tungsten in the WCu specimen on the process was also determined. An increase in cutting forces with decreasing tungsten particle size was observed while a higher percentage of tungsten leads to higher cutting forces. In quasi-static chip forming tests, a scaling of the tungsten particle size also leads to a change in chip formation (Fig. 35) [222].

Another important factor, which has to be taken into account when downscaling the tool diameter, is the dynamic behaviour of the milling process. Biermann and Kahnis [223] investigated the dynamic behaviour by analysing the tool tip motion. They found that at low depths of cut only a few experiments showed the occurrence of chatter. But, also in the experiments where the process was stable, differences in the vibration amplitude and the mean tool tip displacement were noted. A decreasing tool diameter leads to increasing vibration amplitude and tool tip displacement. An example for a surface where chatter occurs during the machining process can be seen in Fig. 36.

Lai et al. [224] developed a model to predict cutting forces and the chip formation in micro milling, which considers size effect, cutting edge radius and minimum chip thickness. The model is based on a modified Johnson–Cook approach using strain gradient plasticity. As a result, the simulation was able to determine the minimum undeformed chip thickness. Also, the proposed model could explain material strengthening behaviours which are found to be the main causes for the size effect. The increasing specific shear energy when machining at undeformed chip thickness smaller than the minimum undeformed chip thickness was largely due to ploughing effects.

7.6. Grinding operations

Size effects in grinding, i.e., the increase in the specific energy and the average specific grain energy with decreasing chip thickness, were investigated in early work by Kannappan and Malkin [225] and by Malkin [226], and more recently, Brinksmeier and Gierzerew [227] discussed about a possible application for a controlled strengthening of workpiece subsurface via work-hardening. Therefore, an advanced grinding process of abrasive material removal, in combination with plastic deformation, has been designed, which could be used successfully for a controlled strengthening of workpiece subsurface. Lowering the cutting speed at constant chip thickness additionally increases the specific grinding energy because of microploughing effects [228]. Heinzl and Bleib [229] showed the promising possibility of using size effects involving the increased specific grinding energy in surface layer work-hardening of metallic parts by showing their effects on the resulting compressive residual stresses.

7.7. Size effects and surface integrity

In recent times, there has been a great interest in studies on surface integrity developed on the machined surface and subsurface, particularly in view of its influence on the life and functional performance of machined components. Over the years, significant effort has been made by the research community in developing qualitative understanding of the surface integrity issues and their controlling factors. Among all well-known surface integrity parameters such as surface finish; macrostructure (10x or less) – macrocracks, macroetch indications, etc.; microstructure – microcracks, plastic deformation, phase transformation, inter-granular attack, pits, tears, laps, protrusions, built-up edge, melted and redeposited layers, selective etching, etc.; micro-hardness, the machining-induced residual stresses have been shown to significantly influence the functional performance of the machined component, particularly the fatigue life. Numerous publications have reported on current and past attempts to develop analytical means to predict the residual stresses in machining in terms of machining parameters (cutting conditions), tool geometry and the work material property, and to devise experimental methods to measure residual stresses in 2D and 3D machining processes. The impact of scaling down the machining operation to micro and even nanolevel machining and the effects of reduced feeds and depths of cut producing large specific cutting energy are still being established. How the size effects will affect the surface integrity and the resulting product life including the overall performance of the machined component has therefore become a major research topic in the research circle. A recent paper by Outeiro et al. [230] discusses some interesting new research directions while the newly formed CIRP Working Group on ‘Surface Integrity and Functional Performance of Components’ has embarked on paving the way for international cooperative research in this area.

8. Conclusions

It is shown by this review that size effects have a strong influence on production processes. The knowledge about size effects is essential for a proper process control. The main features of size effects, which can be divided into three groups of density, shape and structure effects, are:

1. The flow stress of material is influenced by different types of size effects, which are dominant in different size scales. Both an increase and decrease in strength can be observed with increasing size, while the effects are well understood. The extent of the effects increases with decreasing size.
2. In tribology, all size effects observed in lubricated friction can be explained by the lubricant pocket model. Size effects in dry friction seem to be questionable.
3. The formability decreases with decreasing size, making microforming processes more difficult to control. This is especially true, if the grain size to thickness ratio increases.
4. Size effects in forming generate effects on the forming forces and the accuracy of the parts, including spring-back and shape distortions.
5. The most important effect in machining is the increase of the normalized cutting force with decreasing undeformed chip thickness. Despite the fact that the effect itself seems to be always the same (e.g., increase of normalized force) it is of different nature depending on the experimental conditions. A
material under various conditions can be modelled to explain these effects.
6. In forming and in cutting a shape balance effect, e.g., the balance between volume heating by deformation and cooling via the surface plays an important role.

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