

Size effects in manufacturing

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Benefits or difficulties might occur, if processes are scaled down or scaled up. Some sources of the so called size effects, which are responsible for that, are reviewed. These sources can be divided into physical and structural sources. Size effects from these sources are explained and possible remedies are given, using a process chain comprising forming and welding.

1 Introduction

The miniaturisation of components and systems helps to generate new products and to reduce weight of systems having a specific function. Examples for such miniaturized components are hard disks with a size of a coin, cellular phones with integrated features like cameras, hearing aids which can be worn inside the ear and tools for the minimal invasive surgery. There are two possibilities to produce such components. One alternative is the development of new manufacturing processes. This led to extensive research especially concerning the application of lasers in manufacturing [1, 2]. The second alternative is the scaling of the manufacturing processes which are currently used for the production of parts in the so called macro dimension.

Within this paper the following definition is used to separate the macro from the micro world. Subassemblies and components, which are made from parts having a size less than 1 mm in at least two dimensions and a size of less than 5 mm in the third dimension are called "micro components". The geometrical features of these micro components might be much smaller, down to some micrometer.

Another application of the scaling of processes is used for testing parts or processes in a reduced size. This is done to reduce costs for tools and materials in the development stage. This strategy is well known in fluid dynamics to conduct tests on miniaturized samples, which are much cheaper than in the original size. In contrast to this well developed technology this is often not possible in manufacturing processes. An example is the scaling up of sheet metal stamping processes. This is due to the following problem: If the process is scaled down, all tool and work piece dimensions must be reduced by the same factor. If this is done, the processing limits cannot be transferred to the real size parts, as the failure curve in the forming limit diagram is depended on the sheet thickness [3], even if the composition and the surface structure is the same. On the other hand, the test cannot be made with the original sheet thickness and reduced tool size, as the relative bending radii and therefore the failure limit would change. A remedy is the use of FEM simulation instead of physical experiments, which is well developed for deep drawing of parts in the macro size.

If parts are scaled down to the micro size, the scaling process must account for so called size effects, also in a FEM simulation. Size effects are defined as the change in the component or process behaviour when the geometrical dimensions are reduced maintaining the same overall

form. The aim of this paper is to summarize the known size effects and their sources and to give examples for the consequences within the production chain. Chapter 2 summarizes basic sources of size effects. In chapter 3 some typical size effects in the production and performance within a process chain are given.

2 Sources of size effects

2.1 Physical sources

2.1.1 Pure volume size effects

An elemental source of size effects is the pure volume source (PVS). The PVS occurs due to the fact that a decreasing volume of the part decreases the number of micro structural features within this part. The material behaviour changes due to a reduced number of defects or number of grains. This can lead to a change in the failure probability distribution for a specific lot of parts. At very small parts, having dimensions in the range of micrometer, dislocations effects can occur. If the dimension of the part is smaller than the dimension of the Frank-Read-source, the plastic behaviour of the material changes. Whiskers are an example for this effect. The diameter of whiskers is such small that no mobile dislocations and no Frank-Read-source can exist within these single crystals. The result is an extremely high strength which approaches the theoretical shears stress of the material. Pure iron whiskers can reach strength levels of more than 13 GPa [4]. With respect to increasing part dimensions, the PVS can be the source of high residual stresses. This effect is known from welded parts. Residual stresses are developed during the welding process both for small and large parts. While these stresses can relax in small parts, large parts are exposed to large residual stresses which might be detrimental for the engineering properties.

Another positive effect from the PVS can be seen from the aspect of cost. The consumer will pay for a specific function of a component. If this function is realized by smaller parts, other materials might be used due to the very small volume and therefore the reduced weight of the component. Therefore more expensive materials might be used for the production of miniaturized components.

2.1.2 Surface to volume size effect

The surface to volume source (SVS) is relevant for all effects which are dominated by surface effects. The ratio S/V (surface S to volume V) of the part surface to part volume is dependent on the geometry and the size. S/V changes like α/r for primitive geometries (α is 3 for spheres, 2 for cylinders with infinite length, and 6 for cubes; r is the radius and edge length, respectively). Due to that the importance of surface effects will increase like r/α , if the part size decreases.

The SVS is important in processes like heating/cooling, alloying by diffusion, tribology and adhesion. The occurrence of size effects due to the SVS depends, whether the whole or only a fraction of the surface participates in the process. Analytical models might account for the size effects linked to the SVS [5].

One example for a SVS-induced size effect is the heat treatment by patenting, a special treatment for mild steel wires, which gives excellent strength and ductility, but is restricted to small wires due to different cooling conditions when the wire diameter increases.

2.1.3 Forces relation size effect

There are different forces that act on a part beside the processing forces. These are:

- Van-der-Waals-force
- surface tension
- gravitation

Compared to the processing forces in conventional cutting and forming of macro parts these forces can be neglected. This is not true for very small parts, where the process forces approach the value of the above mentioned forces.

Even the relationship between two of the above mentioned forces can result in size effects. Therefore the ratio of the above mentioned forces is called the forces relation source (FRS). A popular example is known from nature, looking at the ability of geckos to climb vertical walls. These animals have some 100.000 very fine hairs at each foot. Being very thin, these hairs adapt excellent to the surface structure of the wall, resulting in very small distances between the end of the hair and the surface. Van-der-Waals forces develop, which are in sum able to overcompensate the gravitation.

One technical example is given in gas metal arc welding (GMAW). The droplet size in metal transition from the welding wire to the weld pool is – in some cases – determined by the balance between the gravitation and the surface tension. As the surface tension depends on the drop radius r and the wire radius r' while the gravitation depends on r^3 , size effects can occur when the wire diameter is changed.

The increasing importance of the adhesion force is used in some MEMS (Micro Electronic Mechanical Systems) to design so called creep motors. These are linear motors with an actor like a 'L', which are in contact to the substrate with the lower tip of the 'L' and the surface of the longer side of the 'L'. Electrostatic forces are used to bend the actor, shifting the tip forward. Reducing the electric voltage leads to a relaxation of the actor to the original shape, while the longer leg of the actor is shifted forward. Adhesion forces secure the position of the actor at the surface, which is not possible with large models of the actor. If the actor is too large, the gravitation would shift the actor in undefined positions, if the MEMS is tilted.

2.2 Structural sources

2.2.1 Grain size to thickness size effect

The grain size of metallic materials is determined by its history. The casting condition, the thermal, mechanical, and thermo-mechanical treatments result in material dependent grain size. The

balance between the coarsening of grains (due to secondary recrystallization) and the refining (due to primary recrystallization) defines the grain size. It is not possible to generate each material with each grain size. Due to that, the grain size can not be scaled down like the part thickness. This results in a grain size to thickness source (GTS) and linked size effects in such processes, where the grain size is important. These are surface roughening effects in forming and cutting and the effective flow stress.

2.2.2 Surface structure scalability size effect

Like the grain size of the material the surface structure is the result of the history of the part. It is influenced by cutting processes and surface roughening, flattening or intended structuring during forming processes. The result of these treatments is also influenced by the grain size, as it has an influence of the elementary processes like grain tilting in forming or elastic springback in cutting operations. In principle, the surface roughness is independent on the part size. It is often not possible to reduce the surface roughness like the part dimension. Due to that the surface structure scalability (SSS) can be the source of size effect. The micro contact remains unchanged, while the macro contact is changed due to miniaturization. Especially in lubrication this leads to a size dependent friction behaviour.

3 Size effects

3.1 Process chain

All products of our daily life are generated within process chains. The performance of the product and the single processes is influenced by all preceding steps. Despite the fact that this is well known, it is often not considered. This is especially true, if undesired properties are visible after one of the last steps in the process chain. For example the distortion after quench hardening, visible after the quenching process, is assigned to the quenching process. Due to that, many efforts are made for an optimization of the quenching process. It was shown [6] that a large fraction of the distortion is already generated during heating before the quenching process, which emphasizes not only the meaning of the heating process, but also that of the residual stresses and inhomogenities in composition, which are generated during the whole process chain. It was shown that the whole process chain must be analysed to understand and reduce the distortion after hardening [7].

This dependence and interrelation is also given for size effects. In order to give an idea of size effects in the product generation and product life a schematical process chain is defined. It comprises forming and welding. A short look on the reliability of the part is given also.

3.2 Forming

3.2.1 Process force

3.2.1.1 Flow stress

The process force in metal forming is strongly dependent on the flow stress of the material. The process force determines the necessary load capacity of the used press and the contact stresses between the tool and the work piece. This in turn has an influence on the elastic springback of the tool and the workpiece – relevant for the part precision – and the friction force.

The GTS results in a size effect, which changes the flow stress (per definition as a material dependent stress, it should be size independent) when the part size is changed. The mechanism of this size effect is due to the transition from a polycrystalline to a single crystalline behaviour [8]. If the grain size is changed at constant part size, the flow stress changes according to the Hall-Petch relationship. The flow stress increases as the grain size is decreased. Surprisingly, the flow stress is reduced, if the grain size is held constant and the part size is decreased. It was shown that this transition occurs not continuously, but above a ratio of grain size to part size of 1/10 [8]. Above this ratio, the part behaves like a polycrystal. The anisotropy of the flow stress, a result of the orientation of the grain compared to the load direction, which is described by the Schmid factor [9], is averaged out. Maybe anisotropic behaviour of the crystals, especially in hexagonal structures, can add to this anisotropy.

If the ratio of grain size to part size raises above the critical value, i. e. there are only a few or even only one grain across the part thickness, the flow stress approaches the value of the single crystal. This is at maximum 1/M smaller than that of the polycrystal, where M is the Taylor factor (M=3.06). The number of glide systems and the orientation, described by the Schmid factor, determine the potential increase of the effective flow stress of the single crystal. The sources of this size effect are described in [10], the effects on forming processes are described in [11, 12]. It was identified that the relative amount of grains which lie at the surface are relevant for these effects [13]. A solution for the calculation of the forming forces is given in [11]. It defines three classes of grains:

- volume grains, which are properly embedded in surrounding grains, resulting in polycrystalline behaviour
- surface grains, which are not restricted in their deformation by other grains at least at one face, resulting in single crystalline like behaviour
- contact grains, which are surrounded by other grains and at one face with a stiff tool. The flow stress would be larger than that of volume grains, if the contact to the tool is ideal. As this is not the case, the contact grains can deform into roughness cavities, resulting in a flow stress behaviour between that of volume and surface grains.

The effective flow stress is determined by a rule of mixture, which takes the relative amount of the three types of grains into account. In macro forming operations, the contribution of the surface and the contact grains is not visible, as their relative amount compared to the volume grains is small. In micro forming the changes in processing forces due to the change in material behaviour can be explained properly [14].

Unfortunately, not all effects can be explained by this model. Contradicting results, which were measured in bending operations [15], might be due to additional effects from the SGS and a change in the strain induced transformation behaviour especially when forming high alloyed steels.

3.2.1.2 Friction

The friction forces F_f are the second important forces in metal forming. These forces are often described using the Coulomb friction law

$$F_f = \mu F_n$$

where μ is the coefficient of friction (COF) and F_n is the contact force. The different contributions to the two components are described in [16]. The normal force is influenced by the effects described in section 3.2.1.1. The SVS might be a source for an increasing importance of the friction force for the process force.

Especially in lubricated friction the SSS leads to changes in the COF. The load bearing capacity of the lubricant is dependent on the possibility to generate a high pressure between the tool and the work piece. If the surface of the work piece and the tool generate closed pockets, the lubricant will be entrapped and generate high pressure. A significant amount of the force between tool and work piece will be transferred by the lubricant. At high viscosities of the lubricant and significant velocities shear forces can be transferred by the lubricant, which might be used for an optimization of the forming process [17]. At low sliding velocities and low viscosities of the lubricant, which are typical in conventional metal forming, no relevant shear stresses will be transferred by the lubricant. A zero friction force results for this zone.

A real surface has different types of roughness valleys. Some of them are interconnected. If these canals end at the free surface, the lubricant can escape from this open pocket. No pressure will be generated inside the pocket. In that case the load between tool and work piece must be transferred by the direct metal contact, leading to a non-zero friction force.

As the size of the open pockets defines a boundary zone of constant size (is the surface structure is held constant), the friction force is determined by high partial friction force in the boundary area and low friction in the area, which has only closed pockets. The size of the boundary area remains constant even when the part size is decreased, if the surface structure is held constant. This can result in a significant increase of the COF with decreasing part size [18].

3.2.2 Accuracy

The GTS, combined with the PVS can be responsible also for a considerable increase of the scatter after forming. The orientation of the grains is arbitrarily distributed. If there are only a few grains within the part, elastic springback and the scatter of forces, due to the effects described in section 3.2.1, will lead to considerable changes of part shape within a manufactured lot. This is so, because the orientation of the few grains changes from part to part, yielding individual effects of local extrusions and springback. The increase in scatter depends on the size of the part and the forming process [8, 19].

The high scatter of micro formed parts are the source for difficulties in welding as described in section 3.3. Currently no adaptive forming processes exist to reduce this scatter. The remedy might be the use of singlecrystalline, nanocrystalline or amorphous metals. If welding of the latter material is necessary, laser spot welding can be a solution, as the amorphous structure is maintained [20].

3.3 Welding

The ability for gap bridging is one of the important features of welding processes. Gas metal arc welding is well known for good performance in this respect. Due to the FRS this process is not scalable down to the micro size. Laser welding can be scaled down to very small dimensions. Deep penetration welding is possible down to penetration depth of less than 80 μm and a seam width of 20 μm [21]. The precondition is a high quality beam, which can be achieved from fibre lasers.

A second demand is to guarantee a zero gap in overlap welding. Due to size effects from the FRS, the rules for gap bridging in macro welding (e. g. gap between the two sheets must be $0.1 s_0$, where s_0 is the sheet thickness) do not apply. As the ratio of the forces from the surface tension and that of the gravitation increases with decreasing size, no gap bridging is observed even for very small gaps in welding of cover layers having a thickness of some 10 μm . The result is lack of fusion, even if the laser beam penetrates the cover sheet and melts the bottom sheet [22]. The cover sheet is melted; maybe the laser beam penetrates the weld and melts the lower sheet. Due to the surface tension the upper melt does not drop down and wets the lower melt, as it is observed in macro welding due to gravitation. Both melts stay separate and solidify without fusion.

In some cases, clamping devices or proper layout of the joint can help to overcome this problem by reducing the gap [23, 24]. Droplet welding uses laser technology to realize a process which is similar to the metal transfer in GMAW, but no direct heating of the work piece occurs. A gap bridging of $0.3 s_0$ can be possible [25]. For larger gaps, spike welding [25] might be used. The process is based on pulse shaping. The initial part of the pulse is smooth, having low intensity. It melts the cover sheet, the melt does not wet the lower sheet. A pulse spike accelerates the melt towards the lower sheet, yielding a sound weld even in positional welding.

3.4 Reliability

After the production the component should have appropriate properties for service. Failures can never be avoided totally. Therefore there will be a Gaussian distribution of failures in a given total volume. This results in two different effects due to the PVS.

With an increasing size of the component, the failure probability of a single part will increase as the probability for a critical error increases. This is a typical problem in welding of huge components. The fatigue strength decreases by a factor of 2, if the plate thickness is increased from 5 mm to 100 mm [26]. The background is described by the Weibull statistics and the fracture mechanics, which can also account for the changing stress condition in thicker welds.

For micro components this failure distribution means that the failure of the parts can show considerable scatter. If single grains are in a weak orientation relative to the applied load, failure will occur at lower loads. Due to that, the failure probability can show similar effects like it was seen for the accuracy.

4 Conclusions

There are different classes of sources for size effects:

- Physical nature: These sources can result in size effects even if all other conditions are held constant. The pure volume effects, the surface to volume effects and the forces relation effects belong to this class. It is not possible to avoid the related size effects, but remedies can be developed by proper processes.
- Structural nature: The sources are due to the fact that the correlation between the dimension of a part and some features can not be held constant in practice. Otherwise, the linked size effects would not occur. Typical sources are the grain size to thickness ratio and the surface structure scalability. Theoretically, it would be possible to avoid the linked size effects, but in practice the necessary miniaturization is not feasible.

Different size effects are known, which are due to one or two sources. There is no general trend concerning

- the occurrence of the size effect with up- or downscaling and
- a positive or negative result due to the size effect.

Some size effects are beneficial, some are detrimental. Some size effects escape, some occur, if the size is reduced. For the detrimental effects different methods are developed to overcome the problems, but much research remains to be done to overcome or at least to master the effects.

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