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THE CURRENT STATE OF ART ON MICROFORMING

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Abstract: The growing utilization of micro parts in various industries has resulted in a notable upsurge in micro production. This trend is especially prominent in sectors such as automotive, aerospace, electronic component manufacturing, and medical device production. This paper gives an overview of researches conducted in certain areas of microforming, including micro deep drawing, micro hydroforming, micro incremental sheet forming, micro extrusion, micro bending, and micro tensile testing.
Keywords: micro forming, micro sheet forming, volume micro forming

1. INTRODUCTION

Micro manufacturing is a specialized field within manufacturing engineering that focuses on producing extremely small and precise components, products, and devices. It involves the fabrication of microscale features and structures, often with dimensions ranging from micrometers to a few millimeters. These products can generally be divided into the following categories: microelectronic products (Fig. 1a), micro optical products (Fig. 1b) and micro mechanical products (Fig. 1c) [1].


(a) (b) (c)

Figure 1. Micro a) electronic, b) optical and c) mechanical products [1]

Microelectronic products are divided into active electronic elements, including transistors and integrated circuits, and into passive ones, which include resistors, capacitors, coils and the like. By merging them into functional circuits, electronic circuits such as stabilizers, rectifiers, oscillators, etc. are obtained. The production of optical elements and devices for transmission and processing of data using light–beam signals is done by micro optics. Micro mechanics is the production of various micro plants and parts such as motors, pumps, turbines, gears, bearings, etc. [1].

Micro manufacturing finds applications in various industries, such as electronics (microchips, sensors), medical (implantable devices, lab–on–a–chip), optics (micro lenses, micro mirrors), and telecommunications (micro–electromechanical systems or MEMS). Despite its potential, micro manufacturing faces challenges related to scalability, cost–effectiveness, and the need for specialized equipment and skilled personnel.

The percentage of sales of micro items is growing year by year, which is due to their increasing utilization in the worldwide market. Figure 2 depicts statistics on the rise of microproduct sales from 2014 to 2020 [2].

The authors [3] define micro manufacturing as:

- micro precision production of macro components,
- micro and nano geometric character production over large and small surfaces,
- micro–dimensional component production,
- production using micro and nano–scale materials,
- manufacturing with a controlled material structure.

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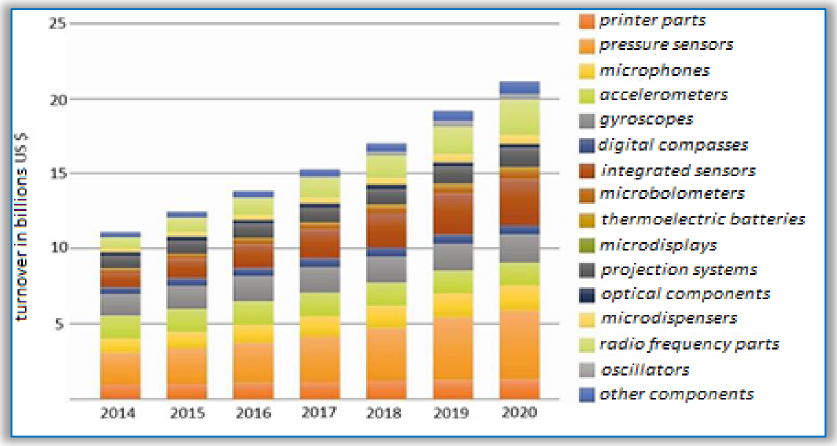


Figure 2. Assessment the size and structure of sales turnover for the period 2014–2020. [2]

Key aspects of micro manufacturing include:

- Miniaturization: Micro manufacturing enables the creation of compact and lightweight products with intricate features. It's essential for industries like electronics, medical devices, aerospace, and automotive, where space and weight constraints are critical.
- High Precision: Achieving precise dimensions and tolerances at the microscale is a fundamental challenge. Micro manufacturing processes require advanced equipment and techniques to ensure accuracy and repeatability.
- Diverse Techniques: Micro manufacturing encompasses a wide range of techniques, including microfabrication, micro injection molding, micro manufacturing, microforming, and micro 3D printing, among others. These methods are tailored to suit specific materials and applications.
- Multidisciplinary Approach: Successful micro manufacturing often requires expertise in various fields, including materials science, mechanical engineering, electrical engineering, and microfluidics. Interdisciplinary collaboration is common.

This paper provides an overview of the recent advancements in the field of microforming. It is an advanced manufacturing process based on metal forming technology that involves the deformation of materials, typically metals, at a microscale level. Microforming has gained prominence due to its applications in various industries and its potential to address the growing demand for miniaturized and precise parts.

There are differences between conventional forming and microforming. This is a consequence of part miniaturization, a phenomenon commonly referred to as the "size effect." The following are some key distinctions between these processes:

- Deformation Mechanism: In conventional forming, the deformation of the material occurs through bulk processes, often involving a large volume of material. Microforming achieves deformations by manipulating a relatively small number of crystal grains within the material, which is why the material cannot be considered homogeneous.
- Tooling and Equipment: Conventional forming typically utilizes larger and more robust equipment and tooling to accommodate the larger workpieces. Microforming requires specialized, high–precision tooling and equipment to work with the tiny dimensions involved.
- Tolerances and Surface Finish: Conventional forming may have more generous tolerances and surface finish requirements compared to microforming. Microforming demands extremely tight tolerances and precise control over surface finishes due to the miniature size of the components.
- Production Volume: Conventional forming is often associated with high–volume production runs of larger components. Microforming is suited for both low and high–volume production, making it versatile for various applications.
- Material Selection: Conventional forming can work with a wide range of materials, including metals, plastics, and composites. Microforming often focuses on metals and specific materials tailored for microscale applications.

— Energy Consumption and Environmental Impact: Due to the larger equipment and material volumes involved, conventional forming processes may consume more energy and have a larger environmental footprint. Microforming processes are typically more energy–efficient and environmentally friendly due to the smaller material volumes and reduced energy requirements.

In the following sections, the outcomes of various studies in the fields of sheet micro–processing and volumetric micro–deformation are presented. In the case of sheet metal processing, studies on micro deep drawing, micro hydroforming, and micro incremental forming of sheet metal have been examined. The emphasis of the bulk micro forming method is on micro extrusion. The impact of the "size effect" on mechanical properties of material was investigated using articles dealing with micro tensile and micro bending methods.

2. RESENT RESEARCHES IN THE FIELD OF MICROFORMING

Micro deep drawing, as one of the micro manufacturing procedures, is used to produce very complex micro–sized parts. In order to examine the influence of the thickness of the part on the properties of deep drawing of copper, the experimental tests shown in the paper [4] were carried out. It has been shown by experimental research and a mathematical model that the size effect occurs when the grain size is kept constant while the dimensions of the sample or workpiece decrease. The paper proposed a model that, based on dislocation density, accounts for the influence of sample dimensions on its mechanical response. The effect of size on micro forming was also dealt with by the authors of the paper [5]. Flexible molding technology provides significant application potential in various areas of production, especially at the miniaturized level. The paper [6] presents the results of finite element simulation and experimental investigations of the micro deep drawing process of 304 stainless steel using a flexible matrix. The experimental apparatus is shown in the figure 3.The results showed that the anisotropic behavior of the steel 304 material plays an important role in the quality of the parts obtained, while the coefficient of friction between the material and the flexible matrix does not play an important role. Similar topics have been discussed by the authors of the paper [7]. The experiment and numerical analysis were also done in the paper [8], in order to determine the deformation behavior of the double layer Al–Cu composite at the micro scale. It has been shown that it is possible to use this composite for micro–processing. For the production of micro components with three–dimensional shapes, metal foils are very convenient and favorable. The authors of the paper [9] carried out micro tensile and micro deep drawing tests on phosphor bronze foils of varying thickness. Research has been carried out in order to characterize existing rolled metal foils at production sites and to clarify the impact of its strong anisotropic properties on the formability of micro sheets. Based on the results obtained, it can be concluded that in addition to anisotropy of the material based on grain texture, it is necessary to take into account geometric anisotropy such as surface topography and damage. The topic of the application of metal foils was also addressed by the authors of the paper [10].

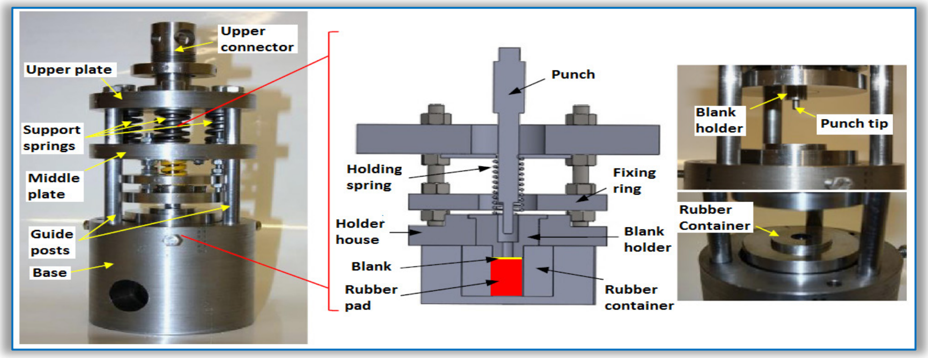
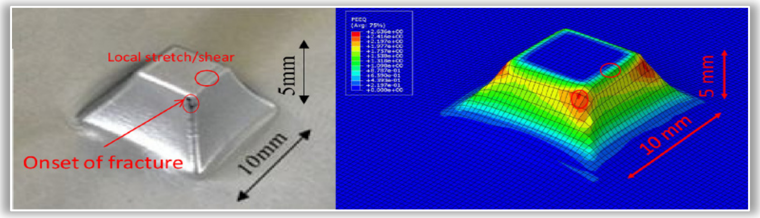


Figure 3. The experimental apparatus [6]

The paper [11] used the piezoelectric actuator as a new approach in this area. As an experiment an analysis of the deep drawing of rectangular parts for 4 different scales is shown. The results shown showed that the thickness of the extracted part decreases, while the force increases, with increasing pressure, which is less pronounced with smaller scales. The spring back increases with the pressure of the holder.

A new approach was also done in the paper [12], where air under high pressure was used as a forming medium. This procedure is called micro pneumatic deep drawing. In order to achieve a high quality of parts, it is necessary to choose the optimal pressure value. In the paper [13] experimental studies of micro hydromechanical deep drawing were done to verify the processing ability of ultra–fine grained stainless steel. Two types of materials were used in this test, ultrafine grained stainless steel and SUS304–H with two types of 20 and 50 μm thick. Experiments have shown that ultrafine grained stainless steel microparts for foil thicknesses of 20 and 50 μm have been successfully obtained, in contrast to SUS304–H material microparts which have only been obtained for thicknesses of 50 μm. The issue of micro hydro forming has also been addressed by the authors of papers [14] and [15]. The study [14] also carried out a test on the SUS304 plate to study the effect of hydraulic pressure on the quality of the drawn Cup. It has been shown that the application of hydraulic pressure can limit the formation of folds and rims, and if ultra–high pressure is used, they can be avoided. The work [15] is based on the processing of copper sheets by the micro / meso scale hydro forming process. Copper sheets of different thicknesses and grain sizes were used. As grain size approached sheet thickness, the maximum deformation height and maximum pressure decreased. Based on failure prediction by applying a modified GTN–Thomason model the parameters were optimized and successful fabrication of PEMFC single polar plate was achieved.

Incremental sheet metal forming is used in the industrial production of parts with simple universal manufacturing tools. The paper [16] minimized this process and studied the new material due to the limitations of the raw material. As a material, copper alloy tape was used. The results showed that the micro incremental sheet forming process is very effective when it comes to identifying material parameters of the law of evolution of Lemaitre's ductile damage. This was observed by comparing the results of process simulations with experiments. The authors of the paper [17] studied the mechanism of deformation in micro single point incremental forming processes. Numerical analysis was done, as well as experimental research (Figure 4), and soft foil made of aluminum 1145 with a thickness of 38.1 μm and 50.8 μm was used as the material.



(a) (b)

Figure 4. Results of the a) experiment and b) numerical analysis [17]

It has been shown that the geometric accuracy of this process varies by region. At the very beginning of the procedure, the dominant area is bending / tightening where the accuracy is affected by the angle at which the test is carried out. Numerical simulation predicted the thickness distribution, which is close to what was obtained by the experiment. Each distribution clearly shows three regions with different deformation mechanisms: bending / tensile, shear, and tensile/ shear, with the last region being characteristic only of the micro scale. A similar problem was addressed by the authors of the paper [18], where the process of micro single point incremental forming of metal foil into a complex three–dimensional shape was examined. The experiment was performed using a tool with a hemispherical tip shape, moving along a predefined tool path. As a material, 50 μm thick foils of Al 1100–O and Al 5052–H19 were used. The forming ability of the foil material Al 5052–H19 has been quantified with regard to determining the maximum wall angle that can be successfully formed by this procedure. The maximum wall angle of 41.8° achieved with the funnel experiment is less than that achievable for parts of the macro scale. In experiments with pyramid–shaped parts, an unusual form of rotation was discovered, which occurs due to an increase in step size and bending of the tool against the direction of movement of the tool. This can be eliminated by making stiffer molding tools or improving the tool movement itself. The work has proven that the developed settings give reliable and repeatable results, which once again confirmed the possibility of using this micro forming process. In order to determine the mechanical characteristics of micro parts, mechanical micro tests of these parts were carried out. Works [5], [19], [20], [21] and [22] show the results obtained by micro tensile, while the authors of the papers [23], [24], [25] and [26] analyzed the micro bending.

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Micro extrusion, as one of the areas of volume micro forming, has been analyzed in papers [27], [28] and [29]. As in all micro forming processes, so in this one, the size effect affects the processing process itself. The aim of the paper [27] was to precisely examine the effect of size and the effect of friction on material pressure and flow, as well as to further identify the actual flow pressure in micro–extrusion by filtering the friction effect. The experiment was performed on five samples with different diameters. Based on the results obtained, it can be concluded that the effect of friction on the voltage is very small in the initial phase of deformation. When increasing stress there is an increase in the contact area between the tool and the samples, leading to an increase in and a friction effect. The increase in the friction effect adversely affects the flow of the material, that is, there is a decrease in it. Also, it has been shown that sample size affects the stress in the material flow, i.e. by reducing sample size the stress values also decrease. For the purpose of similar analysis of this process, the paper [28] developed a general purpose tool for forward extrusion, backward extrusion, forward rod – backward can extrusion and double cup extrusion. Local deformation occurs when only a few grains enter the micro–sized cavity, which occurs when grains are larger. Also, in the case of bulkier grains, a large number of slips occur that pass through the grain boundary to achieve stress continuity. This leads to a blurred grain boundary. In double cup extrusion process, there may be a decrease in the size of micro parts leading to an increase in interfacial friction between the tool and the workpiece. It can be concluded that there is an interactive effect of interfacial friction, plastic properties of micro parts, grain size and part size on deformation loading and geometry of micro–shaped parts. The friction at the phase boundary is higher in the micro extrusion process compared to the classical extrusion process. In the paper [29] an analysis was made of the influence of grain size and workpiece dimensions on the material in the open–type micro extrusion process. The work itself deals with both the process of micro extrusion as well as the process of micro forging. It is observed that extrusion processes, i.e. forging with open molds are not sensitive to the effect of grain size. The reason for this is the conclusion obtained, which is that the location of the neutral plane and its development through parts play a key role. It is the neutral plane, which demarcates the two directions of material flow in these two processes that determines the amount of material flow towards the aperture of the matrix, regardless of grain size. The results of the research also showed that grain size only affects the evolution of the microstructure during the process. In parts with coarse–grained microstructure, there is a delay in the development of the DMZ (Dead metal zone), due to the larger size of dislocation cells in the microstructure. This means that DMZ can be removed on the surface by increasing the initial grain size.

3. CONCLUSION

The aim of this paper was to present recent advances in the field of microforming. The study of microforming has revealed its critical importance in modern manufacturing and its potential to revolutionize various industries. The fundamentals of the microforming process were explained, along with its similarities and differences compared to conventional deformation methods. Through the referenced studies, the size effect, material non–homogeneity, material elastic recovery, and other characteristics specific to these microforming processes were analyzed.

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