COMPARATIVE ANALYSIS OF PARAMETERS AFFECTING MICRO-FORMING PROCESS

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ARTICLE INFO

***Article history*:**
Received: 29.03.2023.
Received in revised form: 01.06.2023.
Accepted: 06.06.2023.

Keywords:
Metal micro-forming
Size effect
Process parameters
Formability
Forming Limit Curve

DOI: https://doi.org/10.30765/er.2163

Abstract:

This review paper provides a comprehensive analysis of the various factors affecting micro-forming and the parameters involved in manufacturing micro-parts. To ensure minimal wear and tear and error-free products, it is important to optimize both the process parameters and framework. The paper aims to highlight the importance of metal micro-forming technology in designing and manufacturing highly precise micro metallic devices, biodegradable implants, micro-pumps, and gears. Through this review paper, readers can gain a better understanding of metal micro-forming, the variables that influence micro-forming and deep drawing, and the process parameters that affect micro-forming and deep drawing technology. Optimizing the process parameters is crucial for the success of micro-forming and can lead to improved product quality, increased production efficiency, cost reduction, process robustness, and improved material properties. The paper specifically discusses the significance of parameters such as blank holder force and size effects on variables that play an important role in optimizing the metal micro-forming process.

1 Introduction

The terminology micro metal forming refers to the manufacture of components or structures with at least two dimensions in micron size. Micro forming is a process for producing very small (micro) metallic pieces, particularly for mass manufacturing, which is required in many industrial and consumer items. The process of moulding and forming sheet metal into various forms and sizes is referred to as sheet metal forming. Sheet metal is a thin, flat piece of metal that may be bent, stretched, and cut into various forms to make a wide range of items [1]. Sheet metal forming is a widely used manufacturing technique in automotive, micro-gear wheels, the medical industry, the optical and medical industry, aerospace, and construction sectors. This involves methods like bending, stretch forming, deep drawing, roll forming, spinning, hydroforming, and stamping. Bulk and sheet metal forming are the two primary categories of micro-metal forming. Miniaturization is progressively influencing the development of a wide range of goods, from automotive, aeronautics, and healthcare to electronics and communication applications [2].

The dynamic market, which necessitates constant advancements in design and fabrication procedures, is one of the industry's primary problems. This entails offering solutions with complicated features while still maintaining high efficiency. Miniaturization continues to become more important in Micro-Electro-Mechanical Systems [2]. Miniaturization involves an interdisciplinary approach, bringing together expertise in electronics and mechanics and physics, chemistry, material science, manufacturing technology, and many other fields. Because these components are in great demand, forming techniques play a key role in this industry because they are unbeatable when huge quantities of parts must be manufactured. Because of its small dimensions, there is a constant shift in grain size, which impacts the product's precision. As a result, dimensional accuracy is a must and must be good.

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Therefore, it is critical to process microscopic components employing integrated micro forming, which contributes to improving tribological characteristics, product precision, and work material formability. Due to micro size constraints, the effect of deformation characteristics in micro forming [2], [3]. The grain size of the specimen, workpiece size, workpiece shape, and component feature size are the major four factors that affect material deformation.

The stability of the micro-forming model, the deformation load, the deformation defect, the dimensional accuracy, the surface polish, and the mechanical characteristics of the deformed microparts (specimen) are all factors that affect the quality of the micro-formed material and how well the system works [3]. The most significant advantage of micro-parts manufacturing is the capacity to make goods with feature sizes of less than 100m. Tiny metal parts and micro-parts manufacturing have been examined for a long period of time, however, attributed to a reduction in size to hundreds of microns, the accuracy has been lowered to a few microns. As a result, the formation of the micro dimension needs day-to-day examination [2]. The key problem with micro-forming concerns the so-called "size effect" caused by the same downsizing. Size impact refers to the perception of unpredictability in process parameters while treating similarly scaled workpieces. These factors separate the presented technique from conventional metal-forming forming processes and substantially impact the potential and limits of this technology [3], [4].

2 Factors affecting micro-forming

The forming threshold of a metal sheet is defined as the point during forming when a concentrated thinning of the sheet begins, eventually leading to a fracture in the sheet. The failure or success of the metal micro-forming process relies on the homogeneous distribution of strain throughout the sheet. The forming limit curve (FLC) shown using surface strains in major and minor directions is used to depict formability. The deformed materials are considered homogeneous in conventional metal forming procedures. They are heterogeneous in micro-forming operations due to the comparatively high grain size to billet volume. The grain structure of the billet becomes increasingly heterogeneous as the grain size rises, and the material exhibits anisotropic behaviour in the sub-millimeter dimensional range. The anisotropic behaviour of the workpiece material might affect local deformation processes directly.

2.1 Impact of flow stress

Flow stress plays a critical role in micro-forming, which is a manufacturing process that involves forming small parts with dimensions on the micro-scale (i.e., less than 1 mm). Flow stress refers to the resistance of a material to plastic deformation during the forming process, and it is a function of several factors such as material properties, temperature, strain rate, and microstructure. Multiple researchers have studied the influence of size on flow stress using compression and tensile test on different size-scaled specimens with varied grain sizes and properties. With the increase in grain size, the stress decreases [5]– [7]. Reducing the size of the specimen and increasing the grain size results in a decrease in flow stress. Both macro and micro-sized specimens are influenced by grain size, but the impact of specimen geometry size is only noticeable when the cross-sectional area of the specimen contains less than 10 grains. This is due to the reduction in grain boundary-strengthening activity.

The atoms in the grain's core have a crystalline periodic pattern, while the atoms at the grain boundary are less structured, making their characteristics similar to those of amorphous materials. Given that only a very small quantity of grain participates in the forming action when the material size is scaled down to the micron level, the location, size, and orientation of each grain is critical. Because of the inhomogeneous nature of materials, dispersion of process parameters such as flow stress develops, affecting the process's formability [2]. Surface grains have fewer constraints than internal grains. Due to the difference in the dislocation structure of surface grains and inner grains, surface grains have much lower flow stress. The flow stress of a miniature workpiece may be adjusted by the surfaces as well as the inner grains. When the grain size grows and the specimen size decreases. The workpiece is composed of only a few grains, the size distribution of surface grains increases while the flow stress decreases [2], [8].

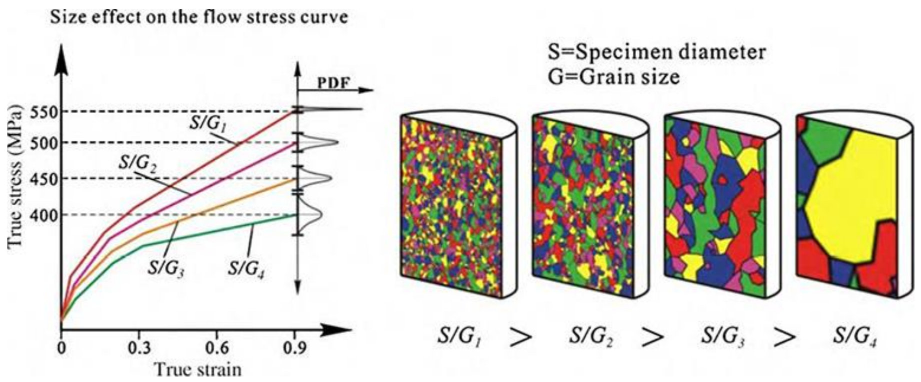

Figure 1. Illustration of flow stress size effect [5].

2.2 Impact of size on formability

Sheet metal formability in micro forming refers to the ability of a sheet metal material to be formed into a desired shape at a micro-scale level, typically with a thickness of less than 1 mm. Micro forming is an important manufacturing process for a wide range of applications, including microelectronics, medical devices, and micromechanical systems. The forming limit curve (FLC) plotted (Figure 2.) using surface strains in major and minor directions is used to illustrate formability. A forming limit diagram is a graphical representation of the boundaries of major and minor stress. It mostly indicates where the local necking begins [1]. In a forming procedure, we know that if the material fails, i.e. cracks occur, it approaches the limit, yet in this case, we normally consider local necking to be undesirable. As a result, FLD is critical in forecasting the forming limit and behaviour of sheet metal. The FLC curve may be seen from two perspectives: the right and the left [1].

Keeler and Backhofen analyzed the right side of the curve and concluded that it is true for both positive major and positive minor strain. Goodwin supplied us with the opposite side of the FLD curve, the left side, and he discovered that the left side is true for positive major strain but not for negative minor strain. The strain ratio of the FLC's left branch may be changed from uniaxial compression (upsetting), and uniaxial tension where $\alpha = -0.5$ to plane strain where $\alpha = 0$. The right-side branch, on the other hand, exhibits strain ratios that span from plane strain ($\alpha = 0$) to equi-biaxial stretching ($\alpha = 1$). We maintain a safety limit of 10%, often known as the safety margin, because we do not want our model to fail abruptly [9]. Any value less than the safety main will not fail and neck. As a result, if a strain value is close to the FLC of the Forming limit diagram, it is prone to necking and failure [1], [9].

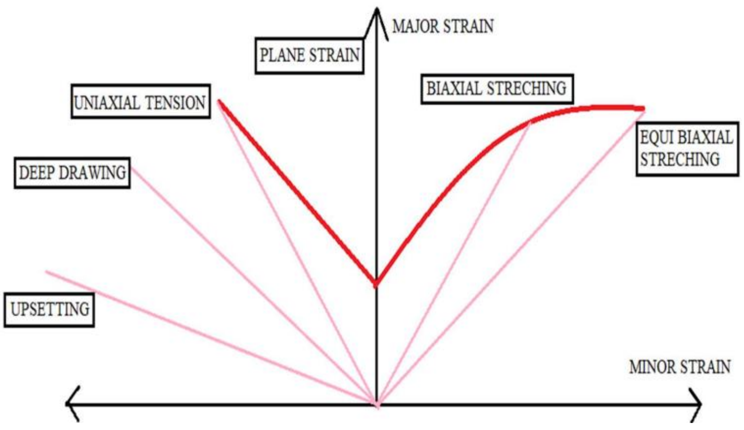

Figure 2. Forming limit diagram [10].

We can therefore determine the FLD experimentally using two well-known approaches. a) Marciniak tests, in which a flat-bottomed cylindrical punch is employed to strain the frictionless in-plane deformed sheet metal. B) Nakajima tests are performed on sheet metal with the hemispherical punch at various sheet widths. To begin the FLD experiment on sheet metal, we will create grids on the sheet. We shall make circular markings of diameter d1 inside the grid. The blank holder will push and apply pressure to the sheet during the process.

After a particular amount of pressure is reached and the sheets are secured, the punch will begin to travel and advance toward the sheet.

The sheet will then be deformed by the punch to form a dome shape. The circles are also stretched, resulting in the form of an ellipse. According to the experimental findings of Marciniak and Kuczyski, the process of loss of local stability of sheet metal during equi-biaxial stretching is distinct from that observed during uniaxial stress of cylindrical specimens. Their study suggests that the limiting strain required for bulging an elliptical or rectangular shape is significantly lower compared to that of a circular shape.

2.3 Impact of size on fracture

Micro-forming processes are susceptible to fracture due to the high-stress concentrations that arise in the deformed region. The fracture can occur in micro-forming due to several factors such as low ductility of the material, insufficient lubrication, inappropriate tooling design, or improper process parameters. Micro-forming fracture behavior may differ from macro-forming fracture behavior [2]. Fracture strain decreases with increasing grain size and decreasing workpiece size. Tensile experiments on wire and thin details revealed this phenomenon. When a fracture occurs in a workpiece, it is typically due to localized shearing within a single grain of the material. This means that the fracture initiates at a small location and then propagates to other areas, causing the material to fail. In micro-forming, the size of the workpiece is significantly reduced, leading to a higher surface area-to-volume ratio. As a result, the material contains more grains, which can act as barriers to the propagation of cracks, making it harder for a fracture to occur.[3], [11].

The fracture strain experiences a rapid decline when the t/d ratio is less than 12. Some researchers performed tensile tests on copper and aluminium wires with bamboo-like grain structures, finding that plastic deformation along the wire was non-uniform and dependent on the grain size and crystalline structure. Experimental studies have shown that as the t/d ratio increases, the fracture strain and the number of micro-voids on the fracture surface decrease. This phenomenon occurs due to the change in the deformation behavior of the material with an increase in t/d ratio. When the t/d ratio is small, the grains in the material are constrained by neighboring grains, leading to a higher number of dislocations and micro-voids that contribute to fracture. As the t/d ratio increases, the number of grains decreases, leading to a reduction in the number of dislocations and micro-voids. Furthermore, when the t/d ratio is small, the fracture occurs due to localized shearing within the grain boundary. However, as the t/d ratio increases, the grains become more equiaxed, leading to a reduction in the number of grain boundaries. This results in a decrease in the number of potential fracture initiation sites, making it harder for a fracture to occur. Therefore, it is crucial to consider the t/d ratio when designing components to minimize the risk of fracture

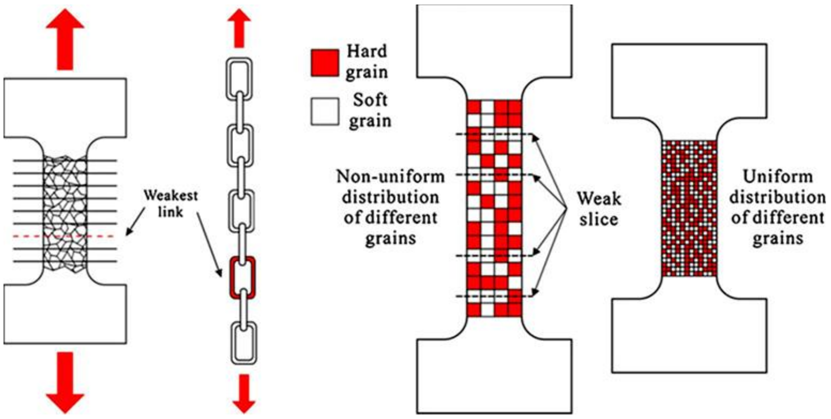

Figure 3. Yielding at the weakest region of stretched material is depicted schematically [13].

By understanding the impact of t/d ratio on the fracture behavior of a material, engineers can choose the appropriate material and optimize the sample geometry to ensure the highest possible fracture resistance.Material yield occurs when all the grains in a portion give, and the first yielding occurs in the weakest area, which typically contains the soft grains. The less the number of grains in the section, the more likely it is to include a significant proportion of soft grains, which reduces fracture strain[3], [12].

Understanding the factors that contribute to fracture in micro-forming is essential for optimizing the process parameters and designing the appropriate tooling to prevent failure and ensure high-quality micro-components.

2.4 Impact of size on elasticity of material

The main challenge in the production of micropart is to maintain the geometrical accuracy of the component micro-formed. As size variances of a few microns are typically necessary in various sectors. The spring-back effect of the material caused by elastic recovery affects the dimensional accuracy of micro-formed components[2]. The form of the compressed workpiece changes from round to irregular as the specimen size is reduced. The irregular shape of the crushed workpiece is caused by the various random characteristics of particle shape, size, and direction. Sliding causes grain deformation. Because macro-scaled crystalline materials are composed of many grains, various attributes can be dispersed randomly and evenly, resulting in isotropic deformation properties. In the manufacturing process of L-bending lead frames, Fu et al. examined the behavior of spring-back. They found that increasing the die angle, die radius, and punch-die clearance led to an improvement in spring-back. When working with sheet metal, the spring-back effect is more significant in the rolling direction than in the transverse direction[2], [14].

2.5 Impact of size on surface roughness

Several researchers have conducted studies indicating that as grain size increases, the surface roughness of various samples also increases. However, this phenomenon is not observed in samples that have been cold-drawn. To determine the extent of the size effect, researchers can use a profilometer to measure the surface roughness of elongated foil samples that have varying thicknesses and grain sizes[15]. The contact between the micro-parts is rough due to the deformation that occurs between the grain surfaces of different locations and the copper sheet that has undergone tensile testing [2]. Experimental studies on steel and aluminium alloys have shown that increasing the degree of deformation and grain size results in an increase in surface roughness. This finding has been consistently observed across multiple studies. Grain deformation and surface roughness are inextricably connected[16]. At the grain boundary, there are three types of deformation behaviors.

This is the most common variation when the average deformation on both sides of the border differs considerably. Just one of the grains experiences considerable deformation. When the quantity of distortion in both grains is almost equal, deformation behavior occurs in the other two types. Grains deform due to slip in this system, and neighbouring grains have different crystallographic locations. As a result, the stresses of contiguous grains are incompatible, and varying degrees of deformation occurs in different grains. Surface grains have fewer constraints, enabling them to move relative to the workpiece's surface due to strain incompatibility. Moreover, deformation is frequently limited to the grain boundary, resulting in groove formation. Urie and Wain investigated groove formation by measuring local elongation in individual aluminium grains[2], [16], [17].

3 Effect of parameters governing micro-forming

The selection of numerous process parameters is critical to the smooth and error-free operation of sheet metal forming. The circular grid analysis and forming limit diagram (FLD) make studying forming in sheet metals easier. This work discusses the aforementioned process factors and their combinations in terms of experimental and analytical methodologies. The purpose of blank holding pressure is to reduce wrinkling or tearing of the workpiece. Amit Jaisingh et al. determined that blank holding force had the greatest impact on the thinning strain. The coefficient of friction, plastic strain ratio, and strain hardening are all changed after thinning. In general, blank-holding pressure is of one of two types: clearance blank-holding and pressure blank-holding. The primary goal of blank-holding pressure is to prevent wrinkling while not interfering with the normal deep drawing process [18].

3.1 Blank holding pressure

The purpose of blank holding pressure (BHP) is to reduce wrinkling or tearing of the workpiece. Blank holding pressure refers to the pressure/load supplied by the blank holder on the blank in order to secure the sheet between the die and blank holder. Amit Jaisingh et al. determined that blank holding force had the greatest impact on the thinning strain. The coefficient of friction, plastic strain ratio, and strain hardening are all changed after thinning. In general, blank-holding pressure is of one of two types: clearance blank-holding and pressure blank-holding. The primary goal of blank-holding pressure is to prevent wrinkling while not interfering with the normal deep drawing process. With mild steel with clearance blank-holding, an initial clearance of 5% is sufficient. Holding 400 psi of pressure on a blank area is adequate to prevent wrinkling. Surpassing this pressure has little or minor effect on the thickness of the final cup or the maximum load of the punch, although thinning is exacerbated with higher loads [18]. In essence, the Blank Holding Force (BHP) plays a critical role in micro-forming by impacting the flow of material, deformation behavior, and tooling requirements.

The effective management and optimization of the blank holding force have the potential to enhance the quality, precision, and efficiency of the micro-forming process. To attain superior quality, precision, and efficiency in micro-forming, it is imperative to ensure appropriate control and optimization of the blank holding force. Nevertheless, it is crucial to acknowledge that a minimum threshold of BHF is necessary to securely retain the sheet metal during forming, thereby preventing slippage or buckling. [18]

3.2 Drawing ratio

In micro-forming, the drawing ratio is the relationship between the initial cross-sectional area of the workpiece and the cross-sectional area of the deformed part after undergoing a drawing process. Its significance lies in its ability to determine the extent of deformation that a material can undergo without failure. A high drawing ratio signifies that a material can undergo considerable elongation without fracturing, whereas a low drawing ratio suggests that the material may experience cracking or tearing during the drawing process. The drawing ratio is a critical parameter in microscale manufacturing and is often used in producing micro-components for medical equipment and electronic devices. Punch load grows almost linearly with blank diameter for any of the drawing circumstances across a large range, with a dip in the area around LDR [19]. In basic words, the limiting draw ratio (LDR) is the mathematical ratio of the maximum diameter of the blank to the punch diameter following a deep-drawing operation, as indicated in the equation below.

The cup's diameter should be such that it does not fail and may be securely pulled without tearing [20]. In microscale manufacturing, the drawing ratio may be a crucial parameter that plays a big role in producing micro-components for medical equipment and electronic devices. Drawing ratio refers to the ratio of the initial blank diameter to the ultimate diameter after the drawing process.

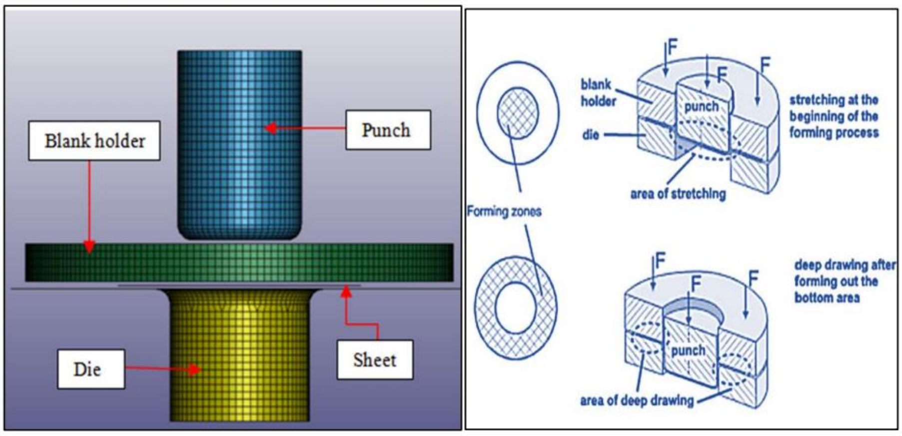

Figure 4. a) Deep-drawing parts b) Forming zones and forming areas in the deep-drawing [21].

The punch load required to shape the blank material demonstrates an almost linear growth pattern as the blank diameter increases across a wide range of drawing circumstances. This increase in punch load can be attributed to the reduction in material thickness during necking, resulting in a decreased force required for further drawing. The Necking-induced Thickness Decrease Ratio (LDR) is identified as a critical parameter in microscale manufacturing that necessitates careful monitoring to prevent material failures, cracks, or tears. By recognizing the correlation between punch load, blank diameter, and drawing ratio, engineering and manufacturing personnel can optimize micro-forming processes, facilitating the production of high-quality components while minimizing material waste and defects. The LDR is an excellent tool for categorizing material formability or drawability. Formability improves as LDR increases and decreases as LDR falls. LDR is a material characteristic whereas the drawing ratio is a geometrical parameter.

$$LDR = \frac{D_{max}}{d}$$

Where 'D_{max}' represents the maximum diameter of the blank and 'd' represents the diameter of the punch [15].

3.3 Punch profile radius

Since fracture occurs at the punch profile radius in a cup design, this profile is the most crucial parameter to properly choose. Because of the bending and unbending of the sheet, the wall of the cup becomes work-hardened and therefore reinforced. On the other hand, unlike cup profiles, punch profiles do not experience work hardening. Thinning rises as the radius of the punch profile grows [17]. Micro-forming, a precise manufacturing technique, is employed to create small-scale components with exceptional accuracy. The punch profile radius plays a crucial role in micro-forming as it directly affects the quality of the formed pieces. Typically ranging from a few micro-metres to tens of micro-metres, the punch profile radius is dependent on the specific application and the material being formed. It governs the curvature of the produced item and significantly influences its surface finish, dimensional precision, and material properties. A smaller punch profile radius generally leads to higher forming forces but can result in improved surface polish and dimensional accuracy. Conversely, a larger punch profile radius reduces forming forces but may compromise surface finish and dimensional precision. Consequently, the optimal punch profile radius in micro-forming is determined by the specific requirements of the application and the material, often necessitating optimization through testing and simulation.

3.4 Die profile radius

The maximum drawing force tends to decrease as the die profile radius increases. If the die profile radius is sharper, the maximum punch load increases overall. If the die profile radius is less than 15 times the blank thickness, the LDR will be reduced. If the punch radius increases more than planned, the punch load and punch distance will increase dramatically. To optimize the die profile radius in micro-forming, several elements must be considered, including material qualities, workpiece thickness, component shape, and forming process parameters such as forming speed and applied force. To describe the deformation behaviour and anticipate the ideal die profile radius for a given set of parameters, computer simulation technologies such as finite element analysis (FEA) can be utilized.

3.5 Anisotropy

The study of a material's microstructure is critical since it determines the material's formability. We have isotropic materials, which have the same characteristics in all directions, or anisotropic materials, which have different properties in different directions [22]. There are two forms of anisotropic materials: a) normal anisotropy and b) planer anisotropy. Normal anisotropy measures material qualities that vary in thickness, whereas planer anisotropy measures material properties that vary in the plane of the material [23]. Anisotropy has a significant impact on the formability and quality of micro-formed products. If sheet metal exhibits high anisotropy, it can demonstrate distinct deformation behaviour in different directions, potentially leading to cracking and other flaws during the forming process. To mitigate the effects of anisotropy in micro-forming, various solutions can be employed. One approach is to use materials with low anisotropy, such as isotropic metals or polymers. Another technique involves optimizing the manufacturing conditions, including annealing temperature and strain rate, to reduce the level of anisotropy in the material. Additionally, numerical simulations can be utilized to predict the material's deformation behaviour during micro-forming and optimize process parameters to minimize the impact of anisotropy.

3.6 Spring back

The spring-back tendency of material during sheet metal forming has been studied, with promising results for reducing defects like wrinkling, earing, damage, crack, and fracture. Spring-back occurs at the V-region and die-lip of the die model, according to the researchers [18], [24], [25]. Spring back can be a significant difficulty in micro-forming since the small size of the workpiece means that even little amounts of spring back can have a large impact on the final part geometry. Many factors influence spring back in micro-forming, including material qualities, forming process parameters, and forming tool shape. Several ways can be used to reduce spring back in micro-forming. One strategy is to use materials with little spring back, such as certain alloys or polymers. Another technique is to limit the degree of elastic recovery in the material by optimizing forming process parameters such as punch velocity, punch displacement, or blank holder force [24], [25].

3.7 Initial blank shape

The impact of the initial blank form and holding force on final product quality, including wrinkling and breaking. In the initial testing, the oval blank shape was shown to have the worst formability in terms of damage and fracture. A silent conclusion was obtained after evaluating the three blank forms oval, oblong, and rectangle [24]. To achieve the successful formation of the micro-parts with the required precision and surface quality, the blank material should have outstanding formability, good mechanical qualities, and a smooth surface finish.

3.8 Radial clearance between punch and die

To avoid ironing, leave enough space between the die and the punch. When ironing, if the clearance is less than the thickness of the sheet of the part being thickened, rubbing or ironing occurs, eventually resulting in uniform thickness of the sheet. The punch force is enhanced during ironing [26]. The radial clearance between the punch and the die in micro-forming is critical in determining the quality and precision of the finished product. The radial clearance is the distance between the punch diameter and the die diameter, and it influences the material's deformation behaviour throughout the forming process. If the radial clearance is excessively great, it might produce excessive material flow and thinning, which can lead to flaws like necking and ripping. On the other hand, if the radial clearance is too small, it can result in significant frictional forces between the punch and the die, which can cause galling and adhesive wear of the tooling surfaces. As a result, there is an optimal range of radial clearance that delivers the highest performance.

4 Conclusion

Micro-forming, the most recent micro-fabrication method for efficiently producing micro components, has lately been in demand due to technological advancements that require tiny parts that may be easily manufactured using the micro-forming process. Studying the experimental output and review by various researchers, this review paper has presented different factors and parameters governing micro-forming along with their effects on the process. The size of the specimen becomes the foremost subject of consideration since this very thing changes the behaviour of the workpiece, and if not considered might lead to the tearing of the specimen. The size affects the properties of the material due to which the accuracy of the micro-formed component will get compromised. The size impacts on flow stress, formability, surface roughness, fracture, and elasticity of the material were thoroughly explored through the examination of many research publications. The selection of a variety of process parameters is crucial to the smooth and error-free functioning of sheet metal forming. Many process factors such as blank holder force, blank form, the radial clearance between punch and die, anisotropy, punch-die radius, and drawing ratio were discussed during the experimental method. The necessity to improve process parameters grows as miniaturization increases. The components may be fabricated with great dimensional precision and a low percent of error if the process parameters and variables impacting micro-forming are well studied.

References

[1] A. Mashalkar, G. Kakandikar, and V. Nandedkar, "Micro-forming analysis of ultra-thin brass foil," Materials and Manufacturing Processes, vol. 34, no. 13, pp. 1509–1515, Oct. 2019, doi: 10.1080/10426914.2019.1655158.

[2] S. K. Sharma, K. B. Kumar, and K. K. Saxena, "Micro Forming and its Applications: An Overview," in Key Engineering Materials, Trans Tech Publications Ltd, 2022, pp. 73–91. doi: 10.4028/p-3u80qc.

[3] K. Mogielnicki, "Numerical Simulation in Microforming for Very Small Metal Elements," in Modeling and Simulation in Engineering Sciences, InTech, 2016. doi: 10.5772/64275.

[4] W. L. Chan, M. W. Fu, and J. Lu, "The size effect on micro deformation behavior in micro-scale plastic deformation," Mater Des, vol. 32, no. 1, pp. 198–206, Jan. 2011, doi: 10.1016/j.matdes.2010.06.011.

[5] W. L. Chan, M. W. Fu, J. Lu, and J. G. Liu, "Modeling of grain size effect on micro deformation behavior in micro-forming of pure copper," Materials Science and Engineering A, vol. 527, no. 24–25, pp. 6638–6648, 2010, doi: 10.1016/j.msea.2010.07.009.

[6] A. Diehl, U. Engel, and M. Geiger, "Influence of microstructure on the mechanical properties and the forming behavior of very thin metal foils," International Journal of Advanced Manufacturing Technology, vol. 47, no. 1–4, pp. 53–61, Mar. 2010, doi: 10.1007/s00170-008-1851-4.

[7] A. Messner, U. Engel, R. Kals, and F. Vollertsen, "SIZE EFFECT IN THE FE-SIMULATION OF MICRO-FORMING PROCESSES"," Journal of Materials Processing Technology J. Mater. Process. Technol, vol. 45, pp. 371–376, 1994.

[8] M. W. Fu, H. Li, J. Lu, and S. Q. Lu, "Numerical study on the deformation behaviors of the flexible die forming by using the viscoplastic pressure-carrying medium," Comput Mater Sci, vol. 46, no. 4, pp. 1058–1068, Oct. 2009, doi: 10.1016/j.commatsci.2009.05.013.

[9] S. K. Paul, "Theoretical analysis of strain- and stress-based forming limit diagrams," Journal of Strain Analysis for Engineering Design, vol. 48, no. 3, pp. 177–188, Apr. 2013, doi: 10.1177/0309324712468524.

[10] R. Amaral, A. D. Santos, C. D. S. José, and S. Miranda, "Formability prediction for AHSS materials using damage models," in Journal of Physics: Conference Series, Institute of Physics Publishing, May 2017. doi: 10.1088/1742-6596/843/1/012018.

[11] J. Q. Ran, M. W. Fu, and W. L. Chan, "The influence of size effect on the ductile fracture in micro-scaled plastic deformation," Int J Plast, vol. 41, pp. 65–81, Feb. 2013, doi: 10.1016/j.ijplas.2012.09.002.

[12] M. Henning and H. Vehoff, "Statistical size effects based on grain size and texture in thin sheets," Materials Science and Engineering A, vol. 452–453, pp. 602–613, Apr. 2007, doi: 10.1016/j.msea.2006.11.113.

[13] W. L. Chan and M. W. Fu, "Experimental and simulation-based study on micro-scaled sheet metal deformation behavior in micro embossing process," Materials Science and Engineering A, vol. 556, pp. 60–67, Oct. 2012, doi: 10.1016/j.msea.2012.06.058.

[14] D. Bin Shan, C. J. Wang, B. Guo, and X. W. Wang, "Effect of thickness and grain size on material behavior in micro-bending," Transactions of Nonferrous Metals Society of China (English Edition), vol. 19, no. SUPPL. 2, Sep. 2009, doi: 10.1016/S1003-6326(10)60098-2.

[15] L. Peng, X. Lai, H. J. Lee, J. H. Song, and J. Ni, "Friction behavior modeling and analysis in micro/meso scale metal forming process," Mater Des, vol. 31, no. 4, pp. 1953–1961, Apr. 2010, doi: 10.1016/j.matdes.2009.10.040.

[16] C. C. Chen and C. P. Jiang, "Grain size effect in the micro-V-bending process of thin metal sheets," Materials and Manufacturing Processes, vol. 26, no. 1, pp. 78–83, Jan. 2011, doi: 10.1080/10426911003636910.

[17] X. Ma et al., "Deep drawing behaviour of ultrafine grained copper: Modelling and experiment," J Mater Sci, vol. 44, no. 14, pp. 3807–3812, Jul. 2009, doi: 10.1007/s10853-009-3515-7.

[18] N. Tiwari, G. Kakandikar, and O. Kulkarni, "Micro Forming and its Application: A Critical Review," Journal of Engineering Research and Sciences, vol. 1, no. 3, pp. 126–132, Mar. 2022, doi: 10.55708/js0103013.

[19] G. Behrens, F. O. Trier, H. Tetzel, and F. Vollertsen, "Influence of tool geometry variations on the limiting drawing ratio in micro deep drawing," International Journal of Material Forming, vol. 9, no. 2, pp. 253–258, Apr. 2016, doi: 10.1007/s12289-015-1228-9.

[20] S. Hussaini, "Determination of the Limiting Drawing Ratio in Deep Drawing Process at Different Temperatures for Austenitic Stainless steel," in 4th International & 25th AIMTDR Conference, Dec. 2012. doi: 10.13140/2.1.1635.2640.

[21] E.Doege and T.Hallfeld, "Metal Working: Stretching of Sheets," Encyclopedia of Materials: Science and Technology, ISBN: 978-0-08-043152-9, p. 5518-5521., 2001.

[22] D. Banabic et al., Sheet metal forming processes: Constitutive modelling and numerical simulation. Springer Berlin Heidelberg, 2010. doi: 10.1007/978-3-540-88113-1.

[23] D.-K. Leu, "The limiting drawing ratio for plastic instability of the cup-drawing process," J Mater Process Technol, vol. 86, pp. 168–176, 1999.

[24] S. Dwivedi, A. Kumar Bhaisare, and A. Singh, "A REVIEW-EFFECT OF PARAMETERS AND ITS ANALYSIS ON FORMABILITY," International Journal of Advance Research in Science and Engineering, vol. 6, no. 05, May 2017.

[25] Z. Xu, L. Peng, and E. Bao, "Size effect affected springback in micro/meso scale bending process: Experiments and numerical modeling," J Mater Process Technol, vol. 252, pp. 407–420, Feb. 2018, doi: 10.1016/j.jmatprotec.2017.08.040.

[26] A. I. O. Zaid and F. A. Hashim, "Effect of Punch and Die Profile Radii on Deep Drawing of Galvanized Steel," Int J Sci Eng Res, vol. 8, no. 1, 2017, [Online]. Available: http://www.ijser.org

[27] R. Uday Kumar, "COMPARATIVE STUDY ON LIMITING DRAWING RATIO OF Al 1100 AND PURE COPPER," vol. 11, 2020, [Online]. Available: www.jespublication.com

[28] H. Ike, "Surface deformation vs. bulk plastic deformation - A key for microscopic control of surfaces in metal forming," in Journal of Materials Processing Technology, Jul. 2003, pp. 250–255. doi: 10.1016/S0924-0136(03)00080-3.

[29] J. Giboz, T. Copponnex, and P. Mélé, "Microinjection molding of thermoplastic polymers: Morphological comparison with conventional injection molding," Journal of Micromechanics and Microengineering, vol. 19, no. 2, 2009, doi: 10.1088/0960-1317/19/2/025023.

[30] S. A. J. Jahromi, A. Nazarboland, E. Mansouri, and S. Abbasi, "INVESTIGATION OF FORMABILITY OF LOW CARBON STEEL SHEETS BY FORMING LIMIT DIAGRAMS *," 2006. [Online]. Available: www.SID.ir

[31] W. L. Chan and M. W. Fu, "Experimental studies and numerical modeling of the specimen and grain size effects on the flow stress of sheet metal in microforming," Materials Science and Engineering A, vol. 528, no. 25–26, pp. 7674–7683, Sep. 2011, doi: 10.1016/j.msea.2011.06.076.

[32] M. Tisza and Z. P. Kovács, "NEW METHODS FOR PREDICTING THE FORMABILITY OF SHEET METALS," 2012.

[33] A. I. O. Zaid, "Deep drawing mechanism, parameters, defects and recent results: State of the art," in IOP Conference Series: Materials Science and Engineering, Institute of Physics Publishing, Sep. 2016. doi: 10.1088/1757-899X/146/1/012009.

[34] J. Han, J. Zhu, W. Zheng, and G. Wang, "Influence of metal forming parameters on surface roughness and establishment of surface roughness prediction model," Int J Mech Sci, vol. 163, Nov. 2019, doi: 10.1016/j.ijmecsci.2019.105093.

[35] W. L. Chan, M. W. Fu, and J. Lu, "The size effect on micro deformation behaviour in micro-scale plastic deformation," Mater Des, vol. 32, no. 1, pp. 198–206, Jan. 2011, doi: 10.1016/j.matdes.2010.06.011.

[36] H. Yin, Z. Jiang, H. Xie, F. Jia, X. Wang, and C. Zhou, "Micro forming of metallic composites," in Procedia Manufacturing, Elsevier B.V., 2018, pp. 1429–1436. doi: 10.1016/j.promfg.2018.07.338.

[37] C. Pradeep Raja and T. Ramesh, "Influence of size effects and its key issues during microforming and its associated processes – A review," Engineering Science and Technology, an International Journal, vol. 24, no. 2. Elsevier B.V., pp. 556–570, Apr. 01, 2021. doi: 10.1016/j.jestch.2020.08.007.

[38] A. Mashalkar, G. Kakandikar, and V. Nandedkar, "Micro-forming analysis of ultra-thin brass foil," Materials and Manufacturing Processes, vol. 34, no. 13, pp. 1509–1515, Oct. 2019, doi: 10.1080/10426914.2019.1655158.

[39] T. B. Stoughton, "A general forming limit criterion for sheet metal forming," Int J Mech Sci, vol. 42, pp. 1–27, 2000

[40] G. Patel, K. Ganesh M, and O. Kulkarni, "Experimental and numerical investigations on forming limit curves in micro forming," Advances in Materials and Processing Technologies, pp. 1–12, 2020, doi: 10.1080/2374068X.2020.1793268.

[41] O. Kulkarni and G. Kakandikar, “Formability Assessment with Microstructural Investigations for Zirconium 702 Thin Foils: Bio-Material Applications,” Advances in Materials and Processing Technologies, vol. 8, no. sup4, pp. 2367–2377, Nov. 2022, doi: 10.1080/2374068X.2022.2044131.

[42] O. Kulkarni and G. Kakandikar, “Novel product design of tool for investigating formability with microstructural study of bio-material titanium grade-II thin foils,” International Journal on Interactive Design and Manufacturing (IJIDeM), 2022, doi: 10.1007/s12008-022-00903-3.