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FORMABILITY AND SIZE EFFECTS IN MICROFORMING: A REVIEW OF MATERIALS, METHODS, AND APPLICATIONS

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ABSTRACT

Micro-manufacturing has drawn significant global attention regarding manufacturing technologies and procedures. Micro-forming is a highly popular method for micro-manufacturing. Microforming is a process of shaping parts and objects through mechanical deformation, which relies on the properties of materials. A significant amount of attention has been directed towards micro-forming, specifically the deep drawing process, due to its capability to generate a wide range of products, especially in its traditional macro-process. This technique is employed to fabricate the most commonplace objects. The discussion then transitions to the current areas of research that are generating the greatest discussion. Due attentiveness has shown a gap in micro-forming technological improvement that must be filled before it can satisfy the unique demands of industrial applications. This is of utmost importance when it comes to making top-notch end products. Precision-forming machines can manufacture such goods using cutting-edge tooling technology, optimal operating settings, and improved material handling techniques.

I. INTRODUCTION

In addition to being an essential part of modern manufacturing, metal shaping is a sizable business in and of itself. Hundreds of millions of tons of metal go through metal-forming processes every year, all around the globe. In most industrialized countries, the metal-forming sector accounts for around 15% to 20% of GDP. It also serves a social purpose by giving many people a chance to earn an income. The metal forming industry is all about mass manufacturing of both partially finished and fully assembled products. Significant advantages for large-scale R&D may be found in this area, since even little savings per ton can add up to big bucks. To enhance the accuracy of the Forming Limit Diagram, surface strain data were further included.

A circular grid made of foil is essential for measuring surface strain [1]. The forming limit diagram (FLD) is a valuable tool for assessing the formability of a metal cost-effectively [2]. Conducting tests utilizing a hemispherical punch-stretch or a Marciniak cup might result in forming limit diagrams (FLDs). Significant amounts of time and effort were dedicated to developing these experimental approaches. Increasing the efficiency of FLDs is accomplished using analytical approaches. Regrettably, analytical methodologies do not possess the capability to foresee failure precisely. A forming limit diagram, also known as an FLD, is a graphical depiction that depicts the main strains (e1) at the point when localized necking occurs, for each conceivable value of the minor strain (e2) [3].

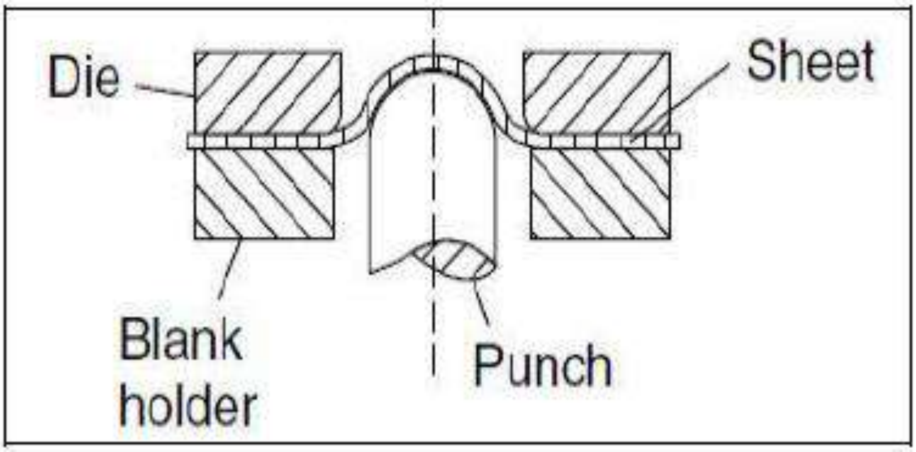

Figure 1: Sheet metal forming.
Source: [4].

Steel facilities, such as factories and plants, are responsible for manufacturing sheet metal, which is used in manufacturing vehicles and their components. Various companies use sheet metal as the primary material for manufacturing various home and commercial goods. Steel makers generate billets that re-rolling mills then shape into various components, including angles, channels, and bars. Incremental forming technique for manufacturing micro-parts that eliminates the need for dies or backing plates [5],[6]. According to [7], this technology may simplify tool manufacture, but it is unsuitable for large-scale production of small components. The micro-sheet metal forming industry utilizes laser forming, a die-less technique, as shown in Figure 1. According to [8] suggest that laser-assisted bending might be used to manage spring-back. The by [9] comprehensively described the process parameters and material requirements involved in laser bending.

The potential use of laser technology in micro-deep drawing methods is now under consideration. In [10] found spark formation more effective than laser forming. Spark formation has several benefits, including its versatility in working with diverse materials, cost-effectiveness, compactness in fabrication equipment, and low energy use.The challenges of microforming, particularly with ultrathin sheets of less than 100 microns, are well recognized in the field, where material deformation can lead to defects such as necking, cracks and wrinkles. As the demand for miniaturization increases in various engineering applications, the need for precise microforming processes also increases. To address this need, the article presents a new tool specifically designed to investigate the formability of thin titanium grade II (TiG-II) sheets, focusing on microstructural behavior. It provides a basis for future research, particularly in applying grade II titanium in micro-sized biomedical components [11].

The study focuses on developing forming limit curves (FLC) for TaRO5200 with a sheet thickness of 80 microns, a fundamental tool for evaluating the formability of microscale materials. This variation suggests that numerical simulations provide a conservative design approach, 15% safer than experimental results. This research's novelty lies in applying the FLC methodology to TaRO5200 and in the detailed microstructural study carried out on the specimens before and after the forming tests. This microstructural analysis provides valuable insights into the material behavior and underlying mechanisms during the formation process, contributing to a deeper understanding of the physics governing the deformation of TaRO5200. According to [12] findings provide a basis for further exploration of biomaterial microforming processes, particularly in biomedical device manufacturing. The research used Simufact Forming V15 software to generate the FLC numerically, and the results were subsequently compared with those obtained from the Nakajima test.

The comparison demonstrated good agreement between the experimental and numerical approaches, and the FLCs produced by numerical simulation were 5% to 12% lower than the experimental results, indicating a safer design margin in the simulations. Additionally, microstructural studies were performed on SS316L sheets before and after forming tests, providing a deeper understanding of the material's behavior during deformation. This comprehensive study provides valuable information on the microforming of SS316L, particularly its application as a biomaterial, and highlights the importance of accurate FLC determination to ensure the reliability of microformed components [13].The study of [12] focuses on the formability evaluation of Zr702 thin sheets, emphasising the development of forming limit curves, a critical tool in evaluating material formability.

The research uses the Nakajima test, performed according to ASTM 2218-14 standards, to experimentally determine FLCs for Zr702 with a sheet thickness of 100 microns. The results of these experimental FLCs were then compared with those obtained through numerical simulations, revealing good agreement between the two methods. In addition to the FLC analysis, a detailed microstructural study of the test specimens was performed before and after the forming process, which provided valuable information on the behavior of the material during deformation. This research contributes significantly to the understanding of the formability and microstructural characteristics of Zr702 in microforming applications, offering a basis for its broader adoption in biomedical fields [14]. Regarding mass manufacturing, none of the technologies mentioned can hold their own. Rather, they should only be used for prototypes or low-volume manufacturing.

Furthermore, certain requirements linked to material characteristics limit the variety of materials used. Remember that the methods mentioned here are complementary, not competing, regarding micro-metal formation. Mechanical micro-sheet metal forming remains the most efficient option for producing micro-components. After 10 years of extensive study and development, the area of mechanical micro-sheet metal forming has yielded a few results. To detect the gaps in the growth of micro-sheet metal, it is necessary to have a mapping that can provide a full picture. This study thoroughly examines the researchers' aims and the necessary conditions for advancing mechanical micro-sheet metal forming technology. To ensure a thorough analysis, the researchers have classified their results based on the characteristics of micro-sheet metal-forming systems, such as the material, process, tool, and machine parameters.

II. THEORETICAL REFERENCE

II.1 SUBTITLE

II.1.1 Materials and Methods

As a result of the shrinking of goods, which allows micro-geometry to carry out product tasks, the present tendency in numerous engineering disciplines is to reduce the size of products. Waste, expenditure, weight, and volume are all areas that will be reduced with this strategy [15]. The microfabrication method may take advantage of metals' outstanding mechanical and functional properties in manufacturing tiny components. This cutting-edge technology is ideal for use in manufacturing since it can be scaled down to the micron size range thanks to this process. According to [16], the market for microelectromechanical systems (MEMS) in micro-manufacturing is anticipated to rise at a compound annual growth rate (CAGR) of 7.5% for medical applications, 43.6% for telecom applications, and 11.0% for industrial applications between the years 2015 and 2024. There has been a significant increase in the demand for small-sized goods because of the growing trend toward downsizing in several different sectors. The medical, precision, communication, micro-electromechanical, and microfluidic equipment industries are especially affected by this phenomenon.

Over the last two decades, there has been significant development in the field of metal micro-forming technology. A variety of research and development activities are included in the study [13]. These activities include surface engineering for die and tooling, micro-hydroforming, embossing, micro-bulk forming, micro-forming with laser help, micro-sintering, and micro-sheet metal forming. The size affected the flow, necessitating an investigation of the deformation behaviours induced by the flow. In this work, we conducted experimental trials to examine the influence of many important factors, including geometry and grain sizes, on the extent of flow-induced defects that arise during the micro-forming process of pure copper. These investigations aimed to ascertain the impact of size on flow-induced flaws [17], [18]. Flow faults in the micro-extrusion process occur due to uneven material flow. This condition is analogous to the one that arises in the macro-forming process.

II.2 SIZE EFFECTS IN MICRO FORMING PROCESSES

An investigation was conducted on the influence of size effects on multi-phase materials, which are affected by the specimen's geometry and grain size. The research demonstrated a reduction in ductility as the size of the specimens was scaled to the millimetre scale range. Moreover, the research highlighted the importance and relevance of having a detailed and intricate surface. It is crucial to consider the impact of size-related factors, such as specimen shape and grain size, especially in materials with several phases, to enhance material characteristics and performance [19],[20]. During the downsizing and micro-component manufacturing process, the usual principles that apply to larger objects are sometimes not applicable.

The side effects, which are caused by the decreased number of grains in the deformation zone, significantly impact formability and might result in fractures during micro forming operations. This emphasizes the need of meticulously considering the impacts of size in micro-forming processes [21]. The work conducted by [22] reveals that the forming limit of copper foils is positively correlated with an increased number of grains. They tested copper foils with 25 and 500mm diameters by subjecting them to bulging, tensile, and bending loads. A spring-back effect, brought on by the smaller particle size and the more significant proportion of surface grains, diminished the hardening capacity of the material, because of that decrease in size, the flow stress changed [23-26].

II.3 DIMENSION EFFECT ON FLOW STRESS

In microforming, the flow stress is significantly influenced by side effects, such as grain size and specimen size [27]. The observation made by [28] stated that, Micro-forming processes need careful analysis of factors, such as the effects of particle size on bulk materials. The behaviour of materials changes as the scale changes, highlighting the need to conduct investigations and analysis. The uniaxial tensile testing trials revealed an inverse relationship between flow stress and strip thickness, indicating that the reduction in flow stress is due to size or scale effects. A surface model was used to clarify these data. The research of [29] dives into the influence of size effects on flow stress inside metal micro-forming techniques, conducting micro tensile tests on pure copper foil to assess the combined impact of workpiece geometry and grain size.

A unique composite material model is built to quantify the strengthening reaction of individual grains included inside a polycrystalline material. Studies have also shown that the flow stress variations are closely related to the ratio of thickness to grain size (T/D) and the interaction between workpiece geometry and grain size [30-32]. A constitutive model was established to support multi-stage microforming. Additionally, incorporating a hybrid material model considering grain heterogeneity, sample thickness, and dislocation structures has proven effective in describing the hardening behavior of grains in microforming processes. These findings emphasize the critical role of side effects and material characteristics in determining flow stress during microforming.

II.4 EFFECTS OF TEMPERATURE ON MICRO FORMING

Temperature control significantly impacts material behavior in microforming processes, influencing material softening and ductility. Higher temperatures enhance ductility, reduce flow stress, and prevent failure. Controlled heating promotes homogeneity, minimizes surface defects, and influences grain size. However, temperature management must balance these benefits with thermal expansion effects for dimensional accuracy. Also, increasing temperature in microforming enhances formability by activating more slip systems, reducing anisotropic behavior, and improving forming homogeneity and reproducibility due to size effects compensation [33].Temperature plays a crucial role in micro-forming processes, influencing material behaviour, flow stress, surface roughness, and fracture mechanisms [34]. High temperatures increase the percentage of elongation in materials like stainless steel-304 foil, affecting tensile strength and fracture patterns. The goal of this study is to look at the mechanical features of a 200 µm thick stainless steel-304 foil by testing it at room temperature (RTT) and at high temperature (HTT).

It was found that the strain rate and temperature affect the flow stress behaviour, surface roughness, microstructural development, and fracture process. High-temperature deformation leads to recrystallization and grain growth, changing surface roughness and fracture mechanism. This analysis can guide the design of micro-sheet metal forming processes for producing micro-parts [35]. In hot embossing of PMMA for microchannel fabrication, temperature variations impact channel dimensions significantly, with optimal conditions identified at 150 °C and 295 kPa [36]. Additionally, in gas-assisted extrusion forming of plastic micro-tubes, higher gas temperatures reduce melt viscosity and enhance flow velocity [37]. An elevation in temperature during cold stamping techniques leads to modifications in the tool-sheet metal tribosystem. This modification can create issues with forming ability, as it affects the level of friction, lubricating properties, and the material's behaviour [38].

Understanding these temperature effects is crucial for optimizing micro-forming processes and ensuring the quality of micro parts. SODICK and WEDM software was used for precision forging micro gear moulds at different temperatures. The surface roughness of the moulds was less than 280 nanometers, and the moulds had a dimensional tolerance that was less than or equal to 2.5 μm. To achieve a surface roughness of 300 nm and a reduction in dimensional tolerance from -38.8 μm to +0.9 μm, the high-temperature forging technology effectively exhibited its outstanding precision [39]. Experimental findings reveal that temperature and grain size considerably impact the deformability of pure copper in micro forming [40]. In another study, Micro-deep drawing (MDD) is used in various fields, including micro-electromechanical systems, vehicle engineering, and chemical engineering. MDD tests on two-layer stainless steel-copper composite foils showed that complete circular cups cannot be formed due to poor formability. An optimal annealing temperature of 800 C was found for high surface quality, indicating the potential of MDD in these applications [41].

By increasing the temperature at which the deformation takes place, a higher number of slip systems within the polycrystalline metal are activated. This results in a shaping process that is more uniform and has improved consistency. In this study, a YAG laser beam is used to apply heat to the workpiece. Additionally, a finite element model (FEM) is developed to simulate the melting and cooling rate (MCWR) of pure copper. A numerical study of surface asperity, which is a sign of material heterogeneity at a small scale, is undertaken, and the results show a high agreement with the findings of the experiments [36]. Forming titanium at elevated temperatures improves its micro-forming behaviour, enhancing formability and forming limits compared to room temperature, as investigated in the study [42]. The work of by [43] presents a micro forming device with controlled heating up to 450°C for medical production, focusing on small, high-precision, low-weight, and high- strength components. The device analyzes magnesium alloy AZ31B flow stress and formability, forming dental components at varying temperatures.

III. MICRO DEEP DRAWING (MDD) PROCESS

Micro deep drawing, it is possible to fabricate hollow objects with slender walls that have a resemblance to miniature cups or boxes. The decrease in the coefficient of friction between the material and the tools due to using lubricant might impact the quality of goods generated in micro deep drawing at a small scale. The research conducted experiments on stainless steel 304 foils with different thicknesses to investigate the influence of blank holder forces and the T/D ratio on the limit draw ratio. The experiments used micro deep drawing and tensile testing. The results indicate that the LDR achieves stability when the T/D (Thickness-to-Diameter) ratio exceeds 10. This suggests enhanced formability and consistent behaviour in a deep drawing to produce micro sheets [44], as seen in Figure 3 and 4. Researchers Zhengyi Jiang and others have shown a micro deep drawing (MDD) simulation, a promising technique for mass-producing complex three-dimensional, tiny metal objects. A Voronoi blank model is constructed for microscale modeling.

This model enables the inclusion of material size effects and authentic microstructures. Simulation results show surface roughness significantly influences springback, drawability, and product quality, making the model accurate and beneficial for MDD process development [45]. Cooper foils are utilized in the microelectrical sector for deep drawing cup-like structures. One research explored micro deep sketching using T2 copper foils and three scale factors. Results revealed the effective formation of pieces with internal dimensions of 0.5, 1.0, and 2.0 mm. The maximum deep drawing force dropped with lower scale factors, and the maximum limit drawing ratio was 2.2 for the experiment with a 0.5 scale factor [46]. The process has also been used to create SUS304 circular cups, with simulation results showing good agreement with experimental data [47]. A novel technique using a floating ring as an assistant die has been proposed for micro-flexible deep drawing, with promising results in producing SS304 micro cups [48].

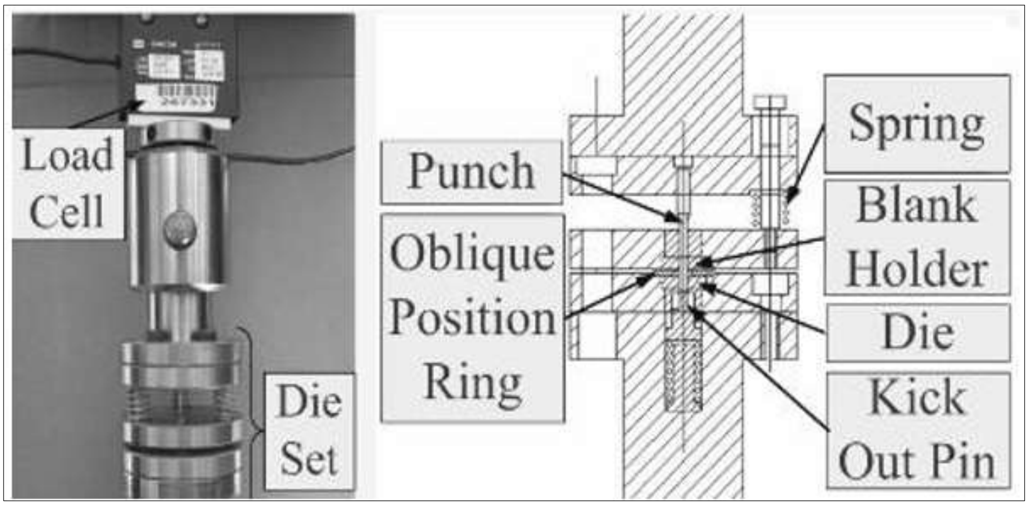

Figure 2: The Setup for Micro Deep Drawing Experiment.
Source: [47].

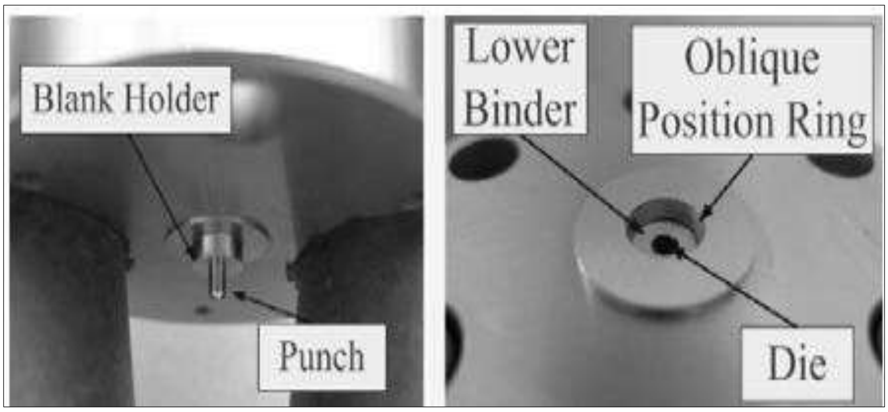

Figure 3: Micro Deep Draw Die Components.
Source: [47].

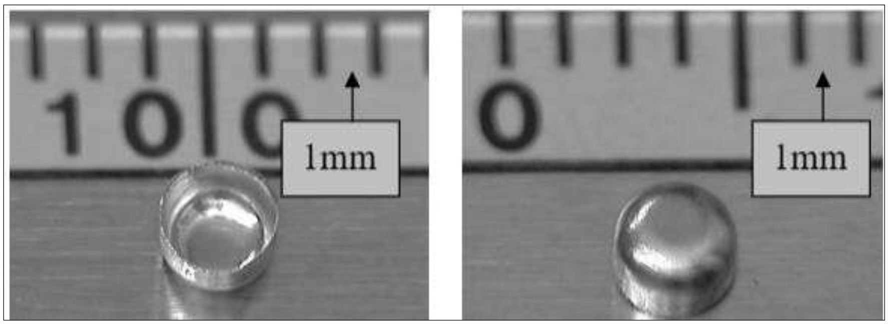

Figure 4: 50µm Thickness Cup (Drawing Ratio = 1.75).
Source: [47].

The study conducted by [49] examines the impact of forming velocity on the quality of micro cup-like products, specifically focusing on stainless steels with different thicknesses. The results indicate that the speed at which the forming process is carried out affects the profile's precision and the surface's quality. The resultant micro cup is rounder and more symmetrical when thicker blanks are used. Wrinkling becomes apparent when using thinner blanks, whereas the surface becomes smoother when the drawing velocity or blank thickness increases. The study by [50] focuses on the micro-deep drawing process of stainless steel 304 foils. The researchers used soft dies made of polyurethane rubber with different hardness levels. The process employs a mobile blank holder backed by a compressive spring.

There is an initial space between the blank holder and the adjustment ring, which controls the forming process against the force exerted by the spring. The calculations and testing examined key aspects such as the kind of rubber, the size of the die, and the scaling factor. These investigations confirmed that the approach can cost-effectively produce high-quality micro-cups. This study examines the micro-deep drawing technique of stainless steel 304 foils using soft dies made of polyurethane rubber with varying degrees of hardness. The process employs a movable blank holder backed by a compressive spring. There is an initial space between the blank holder and the adjustment ring, which controls the forming process against the force exerted by the spring. The models and testing investigated key aspects such as rubber type, die size, and scaling factor, and confirmed that the approach can cost-effectively produce high-quality micro-cups [51].

III.1 ANISOTROPY AND FORMABILITY

Before the 1980s, the yield standards for materials did not include the important anisotropy ratios, which made them less accurate. That's how things were until the 1980s. In 1948, Hills was the only thing that mattered in a few very stressful cases, and it was Hills that gave anisotropic materials the output they needed. Hill added orthotropic materials to the Von Mises criterion. Orthotropic materials are identified by their orthotropic symmetry [52]. According to [53] in his work had discussed the strain-hardening index (equation 1) wasn't the only thing that affected the height of the crack in the Olsen test. Because of this, the strain-rate sensitivity index must also be considered. Researchers found that the material would rise more when the strain-rate sensitivity index (m) was higher for a certain strain-hardening index (n). The sheet metal should be easier to shape now that this is clear [54]. Because of this, steel has a higher strain-rate sensitivity index than aluminum, which means that for a given number of n, it can be shaped better than aluminum.

$$m = \frac{\partial ln l\sigma}{\partial \dot{\varepsilon}} \tag{1}$$

Materials that are light, dense, strong, and easy to shape are now being sought after by the electronics and car industries around the world. Because of this, Tailor Welded Blanks have become more common because they can join different materials in thickness, properties, and surface conditions by shaping or pressing them together. When you use this method, the links between the parts are strong and will last long [55].

According to [56] did four tests on tailor-welded flats to see how easily they could be shaped using two different base materials. Aluminum-killed drawing quality (ASDQ) steel (1.8 mm) and high-strength low alloy steel (2.1 mm) were mixed to make the base. They came up with two reasons why it didn't work. If the main line of the extension was straight across from the weld, a kind 1 failure happened. When this kind of failure happened, the split depended on how well the material could bend and bend again. Furthermore, different sheet metal processes also form materials at very high temperatures, so it is crucial to determine the formability in these situations. Therefore, formability study of such novel approaches is also required to guarantee cost savings, minimal scrap generation, and the ability to apply the forming processes to various materials.

IV. CONCLUSIONS

This review aims to help the reader understand the significance of sheet metal forming techniques and how formability analysis plays a key role in them. The document briefly summarises the different tests used to obtain formability data that can be quantified and determine the forming limits beyond which failure occurs. Over the past 40 years, formability has advanced significantly, and research is still being done to find new materials, thorough testing procedures and tools, and mathematical analyses of the yielding criterion that consider a wide range of additional parameters and their effects on formability. Thus, this research investigates the fundamental aspects of formability and its significance in today's industry. Designing micro-components with high-volume production in mind is essential for micro-manufacturing. Building the failure limit diagram is now the focus of sheet metal research. This is accomplished using numerical analysis, experimental methods, finite element techniques, and sheet metal material management. This study highlights the need for more research into the interaction between materials and handling instruments and micro-forming processes (namely, deep drawing and bending operations).

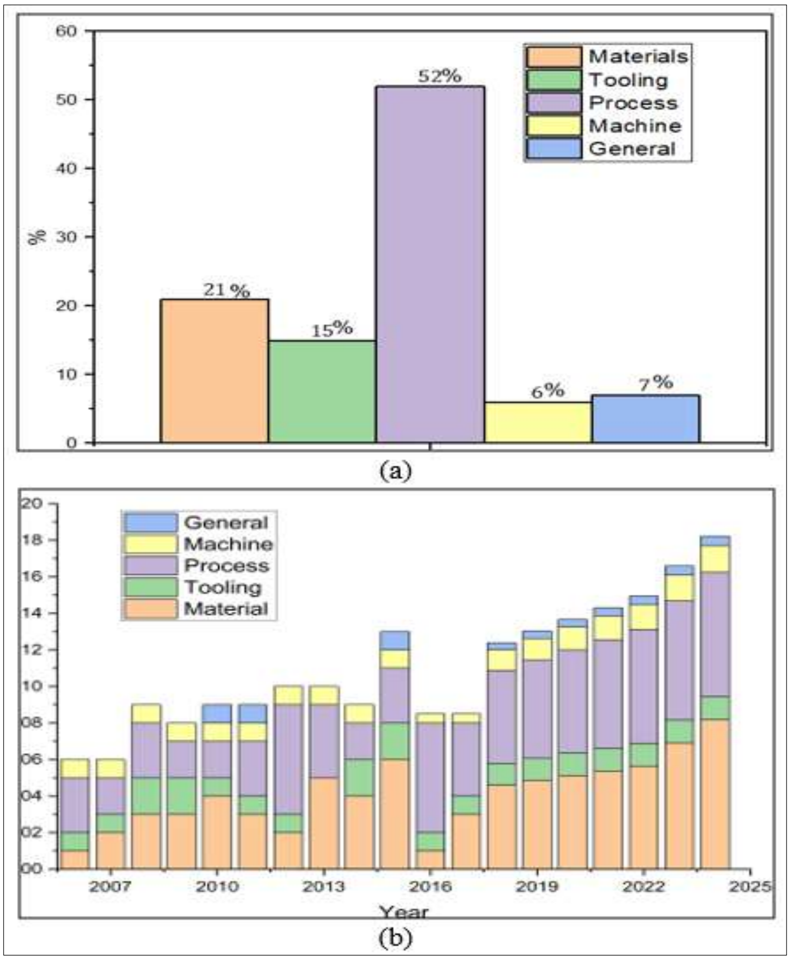

Figure 5: Research focuses on micro-sheet-metal-forming development, (a) in 2001–2017 (b) detailed for 2001–2017.
Source: Authors, (2026).

Figure 5 displays the results of the study's clustering, which shows that the focus was on improving micro-sheet metal-forming technology. Compared to other fields of study, process inquiry is intrinsically more interesting. According to the study's summary, 52% of the research carried out between 2001 and 2017 focused on improving process factors. Researchers are examining the behaviour of material deformation to improve micro-product quality. Nevertheless, many moving parts in manufacturing must be in perfect harmony for the final product to be high-quality. These include superior materials, cutting-edge tools, ideal working conditions, and effective material management. The use of a precision shaping machine might solve these problems. Consequently, more efforts are needed to enhance micro-forming applications in industry. Research product efficacy and process understanding might both be improved by industry collaboration. Many investigations on the micro-forming process have been carried out. However, more efforts are needed to rectify the shortfall in micro-forming technological improvement. The needs of industrial applications can only be satisfied by developing an integrated microforming system.

V. AUTHOR'S CONTRIBUTION

Conceptualization: Gopi Durgam, K K Dhande.
Methodology: Gopi Durgam.
Investigation: Gopi Durgam.
Discussion of results: K K Dhande.
Writing – Original Draft: Gopi Durgam.
Writing – Review and Editing: K K Dhande.
Resources: K K Dhande.
Supervision: K K Dhande.
Approval of the final text: K K Dhande.

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