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Advanced deep drawing methods, challenges, and future scope - A Review

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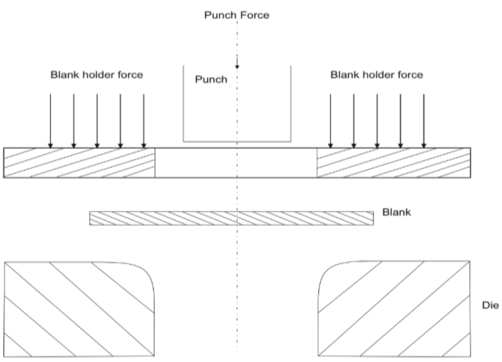

Highlights:

- Advanced deep drawing methods were reviewed.
- Techniques like hydro-mechanical deep drawing (HMDD), magnetic deep drawing using MR fluids, and micro deep drawing were discussed.
- Challenges and future research directions were highlighted.
- Micro deep drawing is a promising area due to the growing demand for micro metallic parts in fields like precision equipment, medical devices, MEMs, communication devices, and microfluidics.

Abstract

One of the important metal forming techniques employed in forming processes of sheet metal is deep drawing. This method allows to produce intricate shapes with fewer flaws. Quality of the deep drawn product depends on the extent of control, exercised by manufacturer, on process parameters of deep drawing. An effective end product with least possible flaws can be manufactured using deep drawing process by effectively controlling the process parameters. This article brings out a consolidated report of the research findings, as reported by researchers across the globe, on recent developments of deep drawing methods with emphasis on quality of deep drawn product. These methods include hydro mechanical deep drawing, micro deep drawing and deep drawing operation using magnet-rheological medium. This paper also presents challenges and scope of future research leading to commercial implementation of recently developed techniques of deep drawing.

Keywords: Deep drawing; Magnetorheological fluids; Hydro mechanical deep drawing; Micro deep drawing; Size effects

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1. Introduction

Apart from the processes like metal casting, metal joining, machining and powder metallurgy, one of the crucial procedures, used to shape metals is metalworking. Nonetheless, the act of shaping metal can be regarded as the original metalworking process, which originated from the basic hammering of copper and gold [1]. It is essential, and the advancement of industry is mostly attributable to this technology's development [2], [3]. In essence, the primary goal of metal forming operations is to attempt to convert a metallic billet into a product of desired geometrical shape [4], [5]. The scarcity of petroleum products is driving up need for additional research on lightweight sheet metals and their application in the automotive industry [6]. One of the mainstays of modern metal forming process is the deep drawing process as shown in **Figure 1**, which turns flat thin metallic sheet into a three-dimensional product which supports a wide range of product applications in various sectors [7]. By virtue of its ability to contribute to improvement in production capacity and energy efficiency, deep drawing technique has gained importance in the present manufacturing scenario [8], [9]. You can do deep drawing on both large and small batch sizes. Numerous industries, including the automotive, packaging, aviation, and model-building sectors, use this technology. Deep-drawn parts for faucets, bathtubs, automobiles, sinks, cooking pots, and yoghurt cups are among the most often produced items. The principle of basic deep drawing process is shown in **Figure 2**.

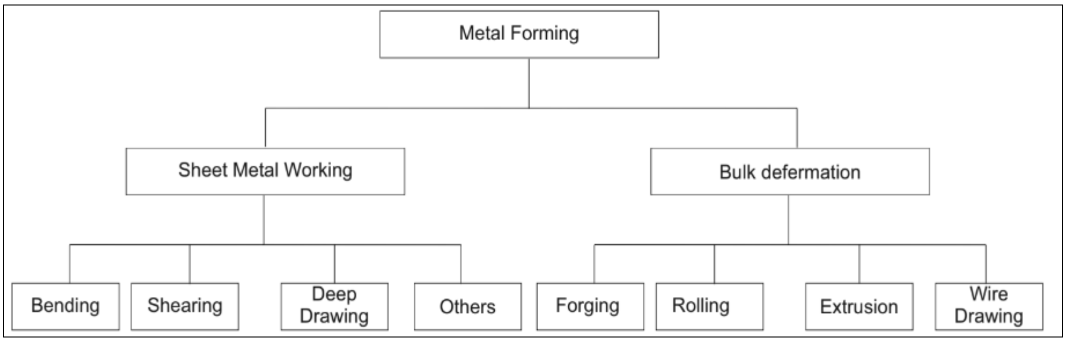

Figure 1. Classification of forming processes

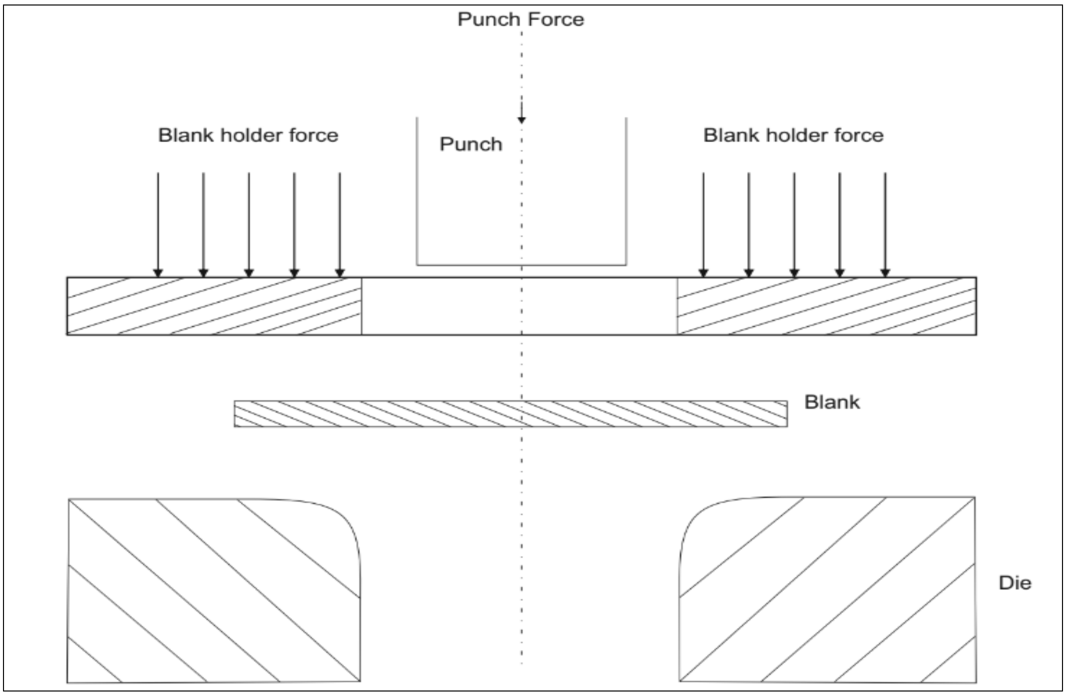

Figure 2. Deep drawing principle

A deep drawn product may fail due to several reasons [8], [9]. Usually, this failure shows itself as ripping, earing, wrinkles, and ruptures. Probability of failure of drawn parts can be minimised by meticulous management of these parameters [10]. These investigations included factors related to- material quality, design of the die along with factors pertaining to operation such as drawing force, drawing ratio and coefficient of friction. Singh et al. [11] reported about the utility of factors of deep drawing such as plunger nose radius, die shoulder radius, coefficient of friction in producing the cylindrical shaped components.

Earlier studies have concentrated on formability of sheets using standard deep drawing and other traditional forming techniques. In addition to these traditional methods, advanced sheet deep drawing process were developed to improve sheet metal's formability and suitable for various applications including in miniaturisation of products like electronic devices, medical equipment, optoelectronics, and sensor technology. Recent researchers also proposed that magnetorheological (MR) fluid for the improvement of part geometry's forming limit and ability. This paper presents hydro mechanical deep drawing method, deep drawing using MR fluids and micro deep drawing methods their applications and challenges and future scope for research.

However, there are some review articles [6]–[8] which are published on this topic; all these articles do not include all the advanced deep drawing methods in their review. Reddy et al. [6]

focused only on the sheet metal formability. Vollertsen et al. [7] reviewed only on micro-deep drawing, and this review article was published in the year 2004. There are several articles published on the topic micro-deep drawing during the last two decades. Hattalli and Srivatsa [8] reviewed the recent advancements on basic sheet metal forming processes such as bending, drawing, blanking, and stretch forming. None of these articles reviewed the advanced deep drawing methods like hydromechanical deep drawing, deep drawing with magneto-rheological fluids, and micro-deep drawing. Hence, the present study focused on these methods. Deep drawing at the elevated temperatures and cryogenic temperatures are not in the scope of this study. This work including the methods to minimize the defects and hence less rejection of formed parts in the industry, and also deep drawing at the optimum forming conditions reduces the energy consumption during the forming processes, addressing the two global issues SDG 9 and SDG 12.
Main objectives of this review study are to present:

- Review the advanced deep drawing methods such as Hydro Mechanical Deep Drawing (HMDD), deep drawing with Magneto Rheological Fluids (MRF) and Micro Deep Drawing (MD).
- Challenges and the ways to overcome these challenges and future directions of deep drawing.
- Suggested future innovative methods of deep drawing.

Scope of this review article is to review the advanced deep drawing methods such as Hydro Mechanical Deep Drawing (HMDD), deep drawing with Magneto Rheological Fluids (MRF) and Micro Deep Drawing (MD). The main challenges addressed in this review article are minimize the non-uniform thickness, wrinkling, earing and enhance limiting drawing ratio and optimization of deep drawing process parameters to achieve the same. Future research of deep drawing can be micro deep drawing and deep drawing at elevated temperatures as well as cryogenic temperatures or even combination of these two as hybrid method of deep drawing.

2. Material and Method

In order to gather up-to-date and pertinent data on the subject at hand, a number of criteria were implemented. English-language journal articles regarding published reviews and experimental works 2000 through 2024 were taken into account. The primary key terms "deep drawing" and "advanced methods" were employed. Related terms like "hydro-mechanical deep drawing," "Deep drawing with magneto rheological fluids," and so on "micro deep drawing. Data from Scopus was considered.

Figure 3 illustrates the growing interest in advanced deep drawing methods using data gathered from the Scopus database using the keywords " hydro-mechanical deep drawing," "Deep drawing with magneto rheological fluids," and so on "micro deep drawing which correspond to the quantity of research publications on this topic published between 2000 and 2024. The quantity of research and review articles devoted to each theme discovered in Scopus between 2000 and 2024 is shown in **Figure 4**.

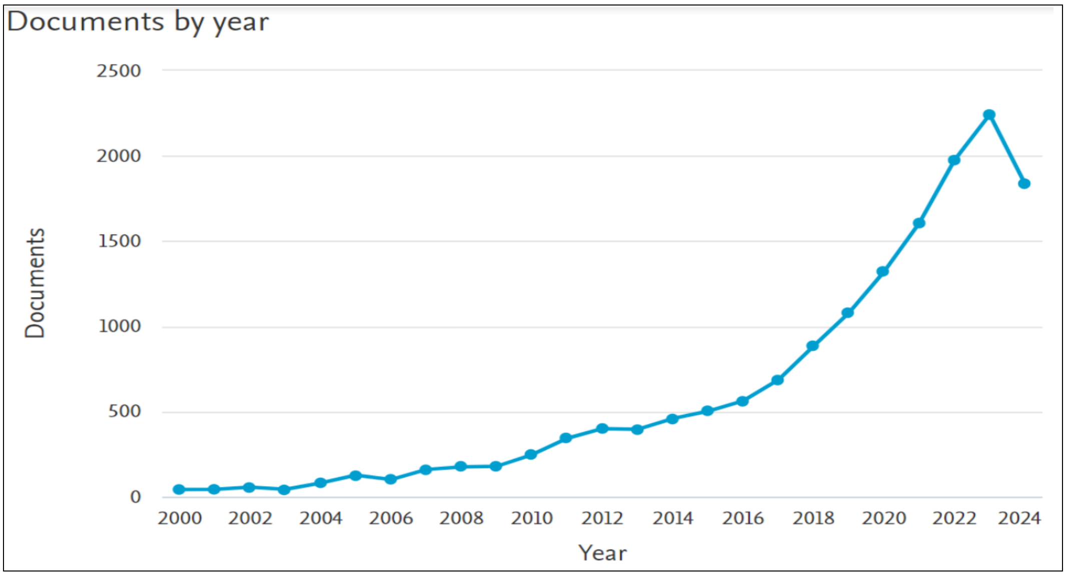

Figure 3. Published scientific papers related to titanium alloys machining (Scopus database)

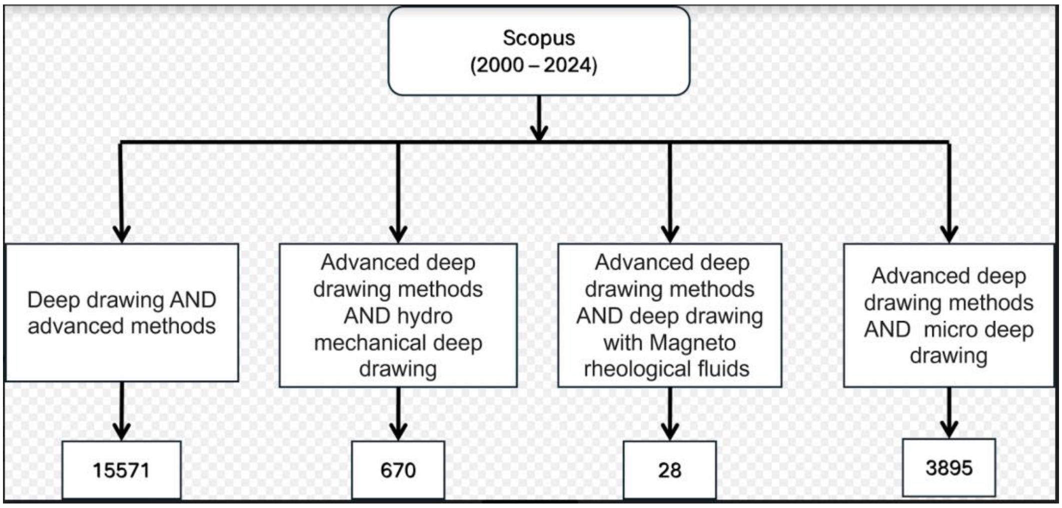

Figure 4. Number of research and review papers for each theme in the Scopus database

3. Results and Discussion

Based on the reviewed studies, the advanced deep drawing methods are hydromechanical deep drawing, deep drawing using mangenotorehological fluids and micro deep drawing. These methods and results of several studies with the challenges and scope for future research so that these methods can be adapted by the industry are discussed below

3.1. Hydro-mechanical Deep Drawing

The formability of light weight alloys can be greatly enhanced by Hydro-Mechanical Deep Drawing (HMDD) technique. Especially for aluminium alloys the formability can be improved by combining the benefits of the procedure and the material. Several sheet hydroforming techniques for the formation of monolithic sheets have been thoroughly developed in recent years and have been investigated by analytical and experimental methodologies. One such methods is hydro-mechanical deep drawing (HMDD). In HMDD method, while the punch presses the blank against the fluid flowing under pressure bellow the blank. The blank takes the impression from the punch.

The process of HMDD along with hydraulic circuit is roughly given in **Figure 5**.

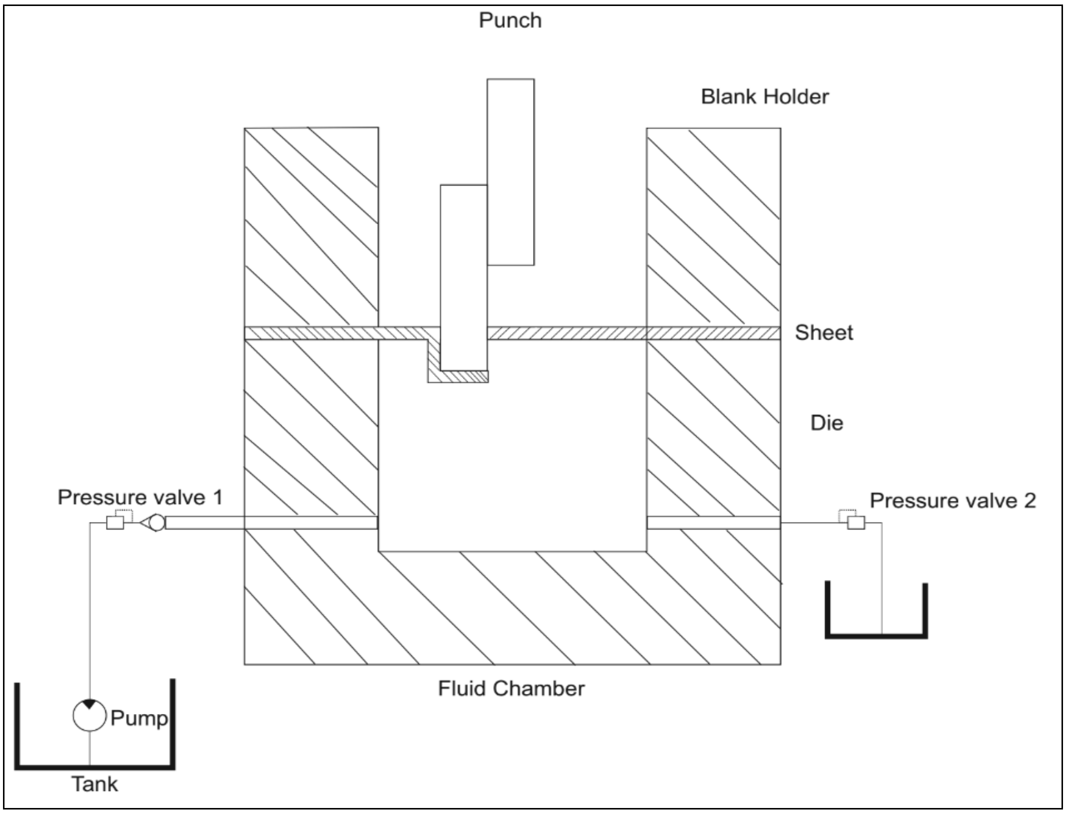

Figure 5. Hydro-mechanical deep drawing (Schematic)

3.1.1. Recent Studies on Hydro Mechanical Deep Drawing

Lang et al. [12] conducted an experimental study on single layer HMDD process. He summarised that with increase in drawing ratio the pre-bulging height, blank holder to die gap and pre-bulging pressure process windows shrink. Fazil and Dariani [13] attempted Finite element simulations of aluminium cups of axisymmetric shape that are manufactured through HMDD process. Objective of this investigation is to determine the safe working zones for certain ratios of fluid pressure to drawing ratio. The limitation of this investigation is the presumption of uniform pressure of the chamber. They demonstrated that higher drawing ratios are possible in HMDD process over traditional method of deep drawing, provided appropriate die radius, chamber pressure at the beginning and conditions of friction are adopted. In a related study, Azodi et al. [14] analytically demonstrated that the critical fluid pressure drops with increasing drawing ratio and corner radius of punch under planar strain assumption. They did this by utilising a tensile instability criterion. An analytical model for axisymmetric parts, that could predict one-layer sheet metal's wrinkling, fracture, and floating condition of a warm HMDD process is presented by Choi et al. [15]. Further they worked for process window for significant parameters like working temperature, pressure of fluid, speed /of punch and holding force of the blank.

With an objective of determining the safe working zones in production of square cups through HMDD, Rahmani et al. [16] attempted for FE modelling. It is reported that with higher friction between punch and black greater is the safe working zone and reverse effect is reported in case of lesser friction. Higher drawing ratios are possible with bigger punch radius. Hitherto Investigations on hydroforming concentrated on monolithic sheets.

Numerical simulation and experimental investigations of multi layered hydroformed sheets is attempted by Lang et al. [17]. This multi layered sheet consists of a thin intermediate sheet with thick sheets on either side. The formability of the thin middle aluminium layer was examined in relation to the anisotropic characteristics of the two outer layers and the arrangement of the layers. It was demonstrated that by considering increased friction coefficients between layers, the formability of the thin middle aluminium layer can be enhanced further. The counter act drawback of inferior formability of the titanium alloy sheet, Tseng et al. [18] used the technique of hydroforming of sheets through creation of two-layer titanium/aluminium battery housing.

Bagherzadeh et al.'s analysis of the instability of hydroformed metal sheets consisting of two layers was published recently [19]. They made theoretical and experimental predictions for the maximum fluid pressure and the forming force. Friction, layer placement, and layer thickness ratio were evaluated in relation to the maximum critical pressure. The analytical model merit is its ability to assess maximum required fluid pressure, but at the same time suffers from disadvantages like its inability to guess entire safe working zone for the given fluid pressure, strain, thickness of layers and formability.

In the recent report, Bagherzadeh et al. [20] carried out three-dimensional finite element simulation of bimetallic laminates by HMDD process, with an objective to depict non uniform distribution of oil pressure during HMDD process. To validate FE results, confirmatory experiments are conducted on generally used laminates made of steel and Aluminium. Influence of different factors like thickness of layer, arrangement of layup on conditions of forming such as formability and process window

The effect of material factors, such as layer thickness and lay-up arrangement, on the forming condition, process window and formability of aluminium sheet was investigated by parametric experiments based on the established FE model. Their findings showed that a built FE model could reasonably forecast the appropriate process conditions needed to achieve the effective formation of bimetallic aluminium /steel sheets. **Table 1** provides the details of various approaches used by researches during hydro-mechanical deep drawing.

3.1.2. Challenges and Approaches in Hydro Mechanical Deep Drawing

To ascertain wrinkling tendency of unsupported part of hydroformed sheet, a model is developed by Chen et al. [21] for assessing critical wrinkling. He also studied the effect of parameters like loading path and pressure of fluid on critical wrinkling stress and circumferential stress. Subsequently, bulging studies were carried out on thin hydroformed sheets. Outcome of these studies showed that the punch's surface quality and axis length ratio significantly affect the fluid pressure. Wrinkling flaws can be completely eliminated by adjusting the fluid pressure. The hydroforming process is also very effective in suppressing wrinkle defects, and it can be controlled to produce well-formed shells with a thickness to diameter ratio of 0.27%.

Table 1. Summary of different approaches used by researchers during hydro mechanical deep drawing

Sl. No	Materials	Method	Results	Advantages	Disadvantages	Ref.
1	Al6016-T4 t-1.15mm	Together with pre-bulging and the standard hydrodynamic deep drawing die set, a 375-ton hydraulic Lagan press was employed.	The maximum drawing ratio obtained 2.46.	Pre-bulging improved forming.	-	[12]
2	Al 100. t-0.74 and 1.24 mm	Changing initial chamber and final chamber pressure	The LDR increases with increasing die profile radius at lower pressures; however, the LDR is unaffected by increasing die profile radius at higher pressures.	With proper parameters in HDD, a greater value of LDR could be achieved.	-	[13]
3	CarbonSteelSt-12, t- 1 mm	100- T hydraulic press of four spacers of gap between the blank holder and die 1.1 mm.	Lower pressures should be applied to avoid rupture at larger drawing ratios.	-	-	[14]
4	CarbonSteelSt-12, t- 1 mm	Pre-bulging pressure is set by the deep drawing process and relief valve-1, while the maximum chamber pressure is set by relief valve-2.	Under particular circumstances, there exists an ideal pre-bulging pressure value that results in the highest possible limit drawing ratio and the largest possible working zone.	A higher drawing ratio and a broader working zone could be obtained by increasing the blank thickness.	Higher pre-bulging pressures result in increased blank strain in the blank holder's contact zone and decreased blank thickness, which ultimately leads to product failure.	[16]
5	Aluminum 2024-O, Glass Fibre and Carbon Fibre	The novel 3A process for creating hybrid parts consists of one layer of 0/90 woven carbon fiber (CF) with Araldite 420, one layer of 0/90 woven glass fiber (GF) with FM 94 TS resin, and one layer of aluminum 2024-O.	Superior mechanical, thermal, and electrical qualities can be achieved in parts that can be produced using the 3A process and used in automotive, aerospace, and military applications.	The 3A approach removes the necessity for repeatedly heating and re-solidifying TP-based composite resin systems at regulated forming pressures and allows any composite or resin material to be positioned anywhere between the metal inter-layers.	Limited in geometrical features.	[17]
6	Composite, annealed aluminum Al-1050, t-0.4 mm and carbon steel St-13, t-0.7 mm,	Hydro-mechanical deep drawing die for drawing with pre-bulging and final fluid pressure by two hydraulic valves.	By laminating aluminum steel sheet, the operating pressure region and carrying load are improved. A thicker steel layer in a laminated Al/St	The approximate operating pressure window was projected by the experimental	-	[19]
	Polyurethane adhesive		sheet increases the operating zone for fluid pressure.	works as a curving border region with a snout that represents the limiting drawing ratio (LDR).	-	
7	Laminated sheet, low carbon steel (St 13) 0.4 mm and Aluminum (AA1050-O) 0.7 mm	50-ton hydraulic press. A fixed gap system with 1.2 mm gap between the blank holder and the die was set by using three stiff spacers	When comparing the AS lay-up to the SA lay-up, the process window and the safe working zone for the fluid pressure are larger in the former. When using the AS lay-up instead of the SA lay-up, higher drawing ratios and LDRs can be obtained.	When applied correctly, the HMDD technique outperforms traditional deep drawing in terms of formability and LDR while creating Al/St bimetallic sheets.	More thinning of the aluminum layer in the SA lay-up at the wall region	[20]

Sl. No	Materials	Method	Results	Advantages	Disadvantages	Ref.
8	2219 aluminum alloy, t-1.484 mm	To deliver the appropriate liquid pressure in the die, a 2000 kN hydroforming press is combined with a high-pressure intensifier.	The wrinkling-free part production process can be achieved by using the appropriate liquid pressure, as demonstrated by the AA2219 hydroforming parts simulation and experimentation	Analytical method can be used for the prediction of liquid pressure for well-formed parts with no wrinkling and rupture.	-	[20]
9	Aluminum alloy 2A12 sheet with a thickness 1.0mm	A 13000 kN double action hydraulic press and a 100 MPa maximum fluid pressure hydro-mechanical deep drawing system.	The tangential compressive stress on the unsupported region can be decreased and the area of the sheet adhered to the punch surface can be increased by using the pre-bulging hydromechanical deep drawing technique to remove wrinkles.	-	Higher chamber pressure will result crack on unsupported region.	[22]
10	Al-Cu-Mn alloy sheet with thickness of 1.45 mm.	10,000 kN hydroforming machine with pre-bulging process design and a 100 MPa liquid pressure intensifier.	The average strain maximum improvement ratio is approximately 75%. Additionally, by employing the pre-bulging technique, the uniform deformation can be enhanced by almost 45%.	The micro hardness of formed part is increased.	-	[23]
11	2024O aluminum alloy sheet with the thickness of 1.0 mm	Multi-step HDD process with different pre-forming depth.	The full cavity pressure in the pre-forming and final forming phases is adjusted within the ranges of 10–15 MPa and 8–15 MPa, respectively, to achieve the desired surface quality and high dimensional accuracy.	This technique can be applied to the integration and precise shaping of workpieces with high drawing ratios and complex features.	-	[24]
12	Stainless steel SUS321 with the thickness of 1.0 mm	HDD with different reverse bulging heights 2.75 mm, 3.75 mm and 5.75 mm, with reverse bulging pressures 1MPa, 1.5MPa, 2MPa, 2.5MPa and 3MPa	At the end of the sheet hydroforming process, the maximum thinning ratio of the sheet is 4.803% with the initial bulging height of 3.75mm and the initial bulging pressure of 2MPa. The highest thinning ratio, in the absence of the initial bulging factors, is 5.123%.	When compared to the standard liquid forming method, the hydroforming process with the first reverse bulging can further reduce the maximum thinning ratio of wall thickness and improve the sheet's forming limit.	-	[25]

The maximum and lower bounds of the forming pressure may be predicted using the theoretical model, and determining the process window of forming is a crucial guiding factor for the forming process experiment of large sized component [26]. Harbin institute of Technology developed large scale fluid forming machine, which is the largest till then, is to coexist with the cracking and wrinkling of large diameter thin-walled deep cavity curved components. This is the first time that hydroforming technology has been used to successfully form large sized aluminium alloy integral parts with maximum diameter of 4m [27]. Influence of pre bulging mechanism in controlling the wrinkling tendency was studied by Lie [22] through experimental and modelling studies.

According to the study, wrinkling flaws can be efficiently eliminated by enhancing contact area of the blank material and punch and diminishing compressive tangential stress of sheet over unsupported wall region [23]. The effect of altering loading path of pressure and parameters related to pre-deformation on sequence of deformation in producing deep drawn tapered/conical parts of uniform thickness with high dimensional accuracy, was studied by Li [24] through numerical simulation results.

For maximising advantages of pre bulging, Lang et al. [28] examined influence of effect of pre deformation on formability of hydroformed components of box shaped sections. The findings demonstrated that pre-bulging heights that are too high or too low are detrimental to formation.

Further, investigations on hydroforming of thin-walled tapered components concluded that uniform wall thickness can be attained by maintaining reasonable pressure and bulging height, while excess pre-bulging pressure led to wrinkles and cracks at the corner of punch [25]. Through a combination of numerical simulation and experimentation, Chen et al. [29] conducted a quantitative analysis of the impact of the effect of pre bulging on formability.

3.2. Deep Drawing using a Magnetorheological Fluid (MRF) Medium

The rheological characteristics of MR fluid, a novel intelligent material, would rapidly alter in response to an externally applied magnetic field [30]. The magnetic particle forms a structure like a chain when it is regularly aligned parallel to magnetic field. With increase in squeezing force, magnetic particle chain will break and continually forms stable clusters [30].

In Hydroforming process, for the first time globally, Rosel et al. [31] proposed the usage of magnetorheological (MR) fluid for the purpose of sealing material over the flange area. They did this by flexibly using the fluid's change in viscosity under conditions of an externally applied magnetic field to raise the sealing limit and the flange area's contact pressure. As a result, the part geometry's forming limit and ability have both improved.

Wang et al. [32], [33] have built and produced a bulging and forming experimental equipment. He carried out a number of studies on the deep drawing process with MR fluid as soft mould and investigated the influence of MR fluid on the deformation pattern of sheet through bulging tests. The experimental findings demonstrated the exceptional effect of adopting an adjustable-performance magnetorheological fluid as the medium for pressure transfer. Indirectly raising strength of magnetic field may enhance the cavity pressure.

According to Wang et al.'s research [34], [35], through control of the strength of external magnetic field greatly improved the sheet metal's stress state and forming properties under external magnetic field conditions. This study looked at the mechanism responsible for effect of varying strength of magnetic field on the performance of bulge formed metal sheets. Wen et al. [36] reported about employing MR fluid for production of tubular components of high precision. Greater degree of uniformity of wall thickness of hydroformed components can be achieved by using more intense magnetic field.

Li et al.'s [37] additional research looked into the use of MR fluid during the thin sheet deep-drawing. The findings emphasised that with the application of magnetic medium in the field of sheet metal forming considerably increases the formability performance of the parts under the atmosphere of MR fluid. Further this use of MR fluid hinders wall thinning at the punch corners. Mu et al. [38] reported application of MR fluid in deep drawing of sheet metal in presence of external magnetic field. Under various circumstances, the inverse bulge pre-deformation deep-drawing composite deformation tests were carried out. Using MR fluid soft mould medium for deep drawing reduces wall thickness variation by 40.8%. Principle of inverse bulgepre-deformation deep drawing is shown sistematicalling in **Figure 6**. According to their findings it is advantageous to have a reasonable height of bulging to enhance the consistency of the wall thickness distribution. **Table 2** provides the details of various approaches used by research during deep drawing with magneto rheological fluids.

3.3. Micro Deep-drawing (MDD)

The need for micro metallic parts has skyrocketed due to continued miniaturisation in a variety of fields, such as precision equipment, medical devices, MEMs, communication devices, and micro-fluidics [39]–[42]. MDD, is a basic micro-forming technique -prominently used for manufacture of cup shaped and hollow thin-walled metallic objects. But, compared to studies on traditional deep drawing, research on MDD is more thorough because of the widespread issue of effects of size present in the micro-scale formation of metals. In order to produce high-quality micro-parts and further the advancement of MDD technology, numerous investigations have been carried out to find out the effects of size in MDD of metals [43]–[45].

3.3.1. Recent Studies on Micro Deep Drawing (MDD)

In their investigations, both analytical and experimental, of the MDD of ASS 304 foils annealed at 900, 950, 1000, and 1050 °C, Chen et al. [46] discovered that, when the foils' thickness remained constant, the limit drawing ratio (LDR) of the foils increases with increase in temperature of annealing. Their study demonstrated that size effects were significant especially for foils with

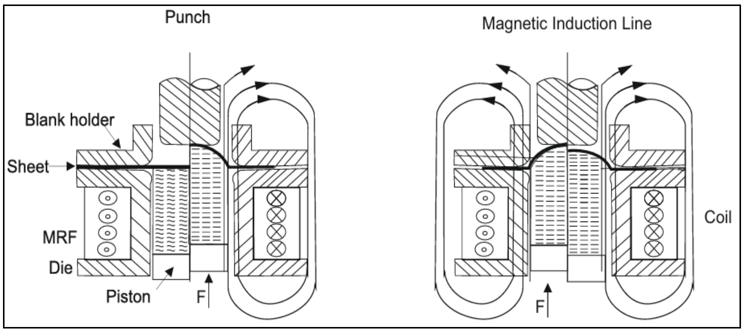

Figure 6. Inverse bulge pre-deformation deep-drawing principle

thickness less than or equal to 100 µm. LDR of ASS 304 foils was influenced considerably by the thickness of foil, ratio of T to D and size of grain. By lowering friction resistance, Ma et al. [47] discovered that, by using a numerical model to study the MDD with radial pressure, LDR of ASS304 cups of circular section increases through suitable gap spacing and radial pressure. MDD was studied by Huang et al. [48] studied MDD with the use of ultrasonic vibration. Results of the study demonstrated that LDR of ASS 304 with 50 µm thickness increases from 1.67 to 1.83 by applying an oscillation amplitude of 2.1 µm.

Table 2. Summary of different approaches used by researchers during deep drawing with MRF

Sl. No	Materials	Method	Results	Advantages	Disadvantages	Ref.
1	DC04, t- 1mm	MRF Basonetic 5030 with external magnetic fields	Better forming	The modification of MRF's fluid characteristics through the application of external magnetic fields and increased sealing effect is indicative of promising fluid behavior.	-	[31]
2	1Cr18Ni9Ti sheet, t- 1mm	Silicon oil-based MR fluid, MRF-J01T with an adjustable DC power supplies electrical current varying from 0A to 15A	Magnetic field strength increases improving the formability of sheet.	Appropriate property of MR fluid can make the strain distribution of bulge specimens more uniform	-	[32]
3	Al1060-O sheet t-0.19 and 0.42 mm	Carbonyl iron particles, silicone oil and addictive.	Remarkable change of sheet forming limit was observed when magnetic field is applied	-	Forming load increased with the iron particle content with a non-linear trend.	[33]
4	Al1060-O sheet t-0.19 mm	Three types of MR fluids of magnetic particle volume fraction of 38%, 43% and 46%	A more consistent thick strain distribution and a higher bulging height can be achieved with the right magnetic particle composition and magnetic field configuration.	More uniform thick strain distribution.	Maximum bulging force increased with the increase of magnetic flux density	[35]
5	Al1060-O sheet t-0.19 mm	The MR fluid of micron size carbonyl iron particles and dimethylsilicone oil of ximeter® pmx-210.	The loading route is directly impacted by changes in the MR fluid's force transmission properties and the friction at the MR fluid/sheet interface.	-	The stress distribution becomes less homogeneous at high magnetic flux densities.	[34]
6	304 Stainless steel sheet t-0.8 mm	Tider MRF 15E, applied currents 0 A, 1A and 2A	Limiting the forming height of the sheet during the deep drawing process by 26.3% when the current is 2A, according to the magnetic medium pressure.	Inhibited the possibility of the wrinkling defect.	-	[36]
7	Al5052 sheet, t-1 mm	MR fluid soft mold forming, and MR fluid inverse bulge pre-deformation deep-drawing composite deformation	When employing MR fluid soft mold medium for deep drawing, the variation in wall thickness is decreased by 40.8% and 37.2%, respectively.	A reasonable bulge height is favorable to improve the uniformity of wall thickness distribution.	When the inverse bulge pre-deformation is too large or too small, the wrinkling defect cannot be suppressed effectively	[37]

A micro hydro deep drawing device was created by Sato et al. [49], [50] and used for ASS 304 foils. It is reported that wrinkling of edges of the drawn cups is suppressed and tribological characteristics can be enhanced with proper control of hydraulic pressure. Luo's study [51], [52] examined hydraulic pressure influence on wrinkling and surface quality of drawn cups of ASS 304. It is concluded that issues related to surface quality of drawn cups can be solved by increasing hydraulic pressure. Luo et al. [53]–[55] annealed ASS 304 foils at 975, 1050, and 1100 °C to produce different grain sizes. An experimental study was conducted to ascertain influence of size of the grain on surface characteristics of drawn cups. They discovered that when grain size increased, the wrinkling phenomena became more noticeable and that foil of ASS 304 annealed at temperature of 975 °C can be utilised to create premium cups by MDD.

According to research findings of Chang and Chen [56], the drawn cups' surface roughness was influenced by grain size, with smaller grains resulting in smoother surfaces. Lee et al. [57] indicated for superior formability and consistency deep drawing behaviour of ASS304 foils should have at least 10 grains throughout their thickness (T/D > 10). Gau et al. [58] devised a combination technique that consists of one MDD and two ironing phases with a view to get a large ratios of cup height to diameter of drawn ASS 304. They advised using ASS 304 foil that has been annealed at 1050 °C to make high-quality cups with precise control over cup height and geometry at the lowest possible cost.

Zhao et al. [59] studied deep drawing of annealed ASS304, annealed at temperatures ranging 700 to 1100 °C, through MDD. They have selected a broad range of annealing temperatures to facilitate the production of various microstructural features. Influence of microstructure on quality characteristics and formability of ASS304 foils was studied. The investigation reported ideal temperatures of annealing for producing high-grade drawn cups.

MDD, or micro-scaled plastic deformation, is a technique for creating sheet metal components that shows promise for mass producing micro-parts made of various materials [60]. High yield, high efficiency, high accuracy, low cost, promising and dependable manufacturing methods are characteristics of MDD processes [61]. Research revealed the importance of scaling effects in the micro-forming that necessitates novel approaches, particularly for tool manufacturing and machine conceptions [62]. Shapes of drawn cups were affected by MDD employing various mail dies [63]. In order to comprehend the impact of size impacts on knowledge, know-how, and technologies, experiments are conducted on MDD at higher height to diameter ratio of cups [58]. A limit drawing ratio of 1.6 is reported by Vollertsen et al. [64] for Aluminium - Scandium alloy foils of 15 µm-thickness. In order to achieve theoretical movement accuracy on the atomic scale, studies utilising a piezoelectric actuator were also carried out during MDD to examine the impact of radii of die and punch on thickness distributions, spring back and punch force [65]. **Table 3** provides the details of various approaches used by researches during micro deep drawing.

3.3.2. Key Issues in MDD

There are several factors that influence the part quality in MDD some of them are size effect, parametric effect, coating and lubrication on die and punch which are briefly explained in this section.

3.3.2.1. Size Effect

Using the micro-deep drawing (MDD) procedure, a huge number of parts with at least two sub-millimetre dimensions for their geometrical feature can be produced. Nevertheless, when the process is shortened, a few things happen. The inherent properties of crystallographic orientation and the size impact that occur during MDD influence the deformation behaviour and may result in draw faults. As the forming process are adjusted up or down, size effects become significant. They are divided into three groups: microstructure size effects, density, and shape. Density size effects are caused by reduction in number of features of object relative to its size. As an object's size decreases, shape size effects arise due to an increase in ratio of surface area to volume. Grain size, roughness of surface and other factors that are not reduced down in proportion to the object's macroscopic size are known as microstructure size effects [64], [66].

CuZn37 foils were used in various annealed settings by Justinger et al. [67] made investigations utilising geometrically scaled deep drawing tool sets with diameters of punch ranging from 8 mm to 1 mm. Within this range, the foil thickness is varied from 0.3 to 0.04 mm. Two distinct size impacts were noted in their study while analysing the MDD process. When compared to the annealed material and smaller scale factors, the highest punch forces were observed irrespective of the scaling factor. In comparison to smaller cups, the punch forces were seen to diminish as velocity increased for the larger cups.

Table 3. Summary of different approaches used by researchers during micro deep drawing

Sl. No	Materials	Method	Results	Advantages	Disadvantages	Ref.
1	Stainless steel 304 foils with four thicknesses 150 µm, 100µm, 50µm, and 20µm	Several types of springs with different spring constants were used to generate different blank holder forces. varied from 2.2 N to 220 N	With the exception of 20µm, LDR increases as grain size increases for foils of the same thickness but reduces as the T/D ratio increases. The thicker foil has a greater LDR for foils with the same T/D ratios or grain sizes.	For stainless steel 304 foils that are not thinner than 150 µm, the maximum draw load and LDR can be determined using the macroscale empirical deep drawing formulae.	The macro scale empirical equations cannot be used to foils with thicknesses of 100 µm or less in order to anticipate micro-deep drawings.	[46]
2	Stainless steel 304 foils of 50 µm, 75µm, and 100µm	A10-kN MTS testing machine equipped with a data acquisition and ultrasound generator set at 2 kW to provide frequencies between 20 and 21 kHz	For 50-µm-thick foils, ultrasonic vibration resulted in an increase in LDR from 1.67 to 1.83, with an amplitude of 2.1 µm. The LDR increased from 1.75 to 1.92 with an amplitude of 4.1 µm for foils that were 75 µm thick. The LDR increased from 1.83 to 2 with amplitudes of 2.1 and 4.1 µm for foils that were 100 µm thick.	By applying ultrasonic vibrations following a micro-deep drawing process, the LDR increased depending on the foil thickness and the oscillation amplitude.	Foils with thicknesses of 50 and 75 µm are not appropriate for an oscillation amplitude of 8.6 µm	[48]
3	Phosphor bronze foils (C5191-H) with thickness of 20 and 50 µm	MHDD die and hydraulic system. a multiaxial servo press for one-stroke forming.	The MHDD apparatus may create a counterpressure with a 1 µm clearance between tools to achieve a consistent sealing and prevent wrinkling with a constant gap of $h = 1.10\ t_0$.	The appropriate counterpressure applied in MHDD can eliminate wrinkling and reduce the frictional drawing force	Forming load increased with the iron particle content with a non-linear trend.	[49]
4	Stainless steel foil (SUS304-H) with a thickness of 50 µm	A desktop servo press machine of the MHDD type, equipped with a pump capable of producing up to 20 MPa of maximum pressure and a load cell capacity of 20 kN.	The fluid pressure required for hydro-dynamic lubrication increases because the contact pressure at the die shoulder increases at small Dp/ t.	MHDD can improve the tribological behavior by inducing lubrications through the application of appropriate fluid pressure.	-	[50]
5	The SUS304 sheets with a thickness of 50 ± 2 µm.	One-stroke blanking-drawing process was applied for the micro hydro deep drawing system.	The development trends for wrinkles and ears shift twice, reaching local maximums inside the critical pressure range. The development trend for wrinkles is the reverse of that of the earings.	-	Because the hydraulic pressure used in the studies was only 30 MPa—less than 10% of the blank's initial yield stress—wrinkling and earing cannot be completely avoided.	[51]–[53]
6	SUS304 stainless steel thickness 0.05, 0.1 and 0.2mm	Micro deep drawing die set in a precision press speed range from 0.01 to 35 mm per second	The greater load was produced by the lower grain size sheet that was received. The surface textures of the as-received sheet with smaller grains were smoother than the annealed sheet with bigger grains.	-	-	[56]
7	Austenite stainless steel 304 sheets with 200 µm thicknesses annealed at 900	For deep drawing, the first ironing stage, and the second ironing stage, respectively, there is one cylindrical punch	This process is a very robust as long as the sheets are annealed at the temperature no less than 900 ◦C for more than 3 min (or T/D < 10).	-	Using this method die fabrication is more complicated and expensive	[58]

Sl. No	Materials	Method	Results	Advantages	Disadvantages	Ref.
	◦C, 950 ◦C, 1000 ◦C, and 1050 ◦C	with a diameter of 2 mm and three female micro dies called Die-1, Die-2, and Die-3.				
8	Cold-rolled ASS 304 foils thickness of 50 ± 2 µm annealed at 900 ◦C, 950 ◦C, 1000 ◦C, and 1050 ◦C	A desk-top servo press machine, model number DT-3AW, with a maximum force and displacement capacity of 30 kN and 40 mm, respectively.	For ASS 304 foils, the best annealing temperatures found in this work are 900 °C and 950 °C in order to make drawn cups with the fewest wrinkles possible using MDD.	-	-	[59]
9	Stainless steel cup measuring 2.5 mm in inner diameter and 0.1 mm in thickness	To allow the drawing force to be divided between the punch nose and the micro-ridges, micro-ridges are placed to the punch nose's surface.	Ideal settings The measurements of the ridge were as follows: ridge height of 0.01 mm, ridge gap of 0.1 mm, ridge nose radius of 0.02 mm, and ridge-to-nose distance of 0.03 mm.	-	-	[61]
10	The stainless steel SUS304 foil with a nominal thickness of 50 µm	MHDD experiments were conducted under different hydraulic pressures using a MHDD system pressure from 5 MPa to 30 MPa at an interval increment of 5 MPa	When the hydraulic pressure increases, the drawn cups' number and height of wrinkles grow first and thereafter diminish.	An rise in hydraulic pressure causes the maximum contact forces and contact pressures on the blank holder and die to drop, extending the tool's service life by reducing wear on the MHDD component.	-	[58]
11	Al99.5, thickness 0.015, 0.02, 0.1 and 0.2 mm	Piezoelectric actuator which is implied as a novel approach in the field of micro deep drawing.	The thickness of the drawn component increases as the drawn radius increases, and the increase in macroscales is greater than the growth in microscales. As the drawn radius increases, springback increases as well.	-	-	[65]
12	Austenitic stainless steel (ASS) 304 foils with a thickness of 50 µm	A desk-top servo press machine, model number DT-3AW, with a maximum force and displacement capacity of 30 kN and 40 mm, respectively.	The study determined that 900 and 950 °C are the ideal annealing temperatures to minimize wrinkling and enhance the quality of drawn cups.	-	As-received ASS 304 foil has a poor formability and cannot be used to form a cup using MDD	[59]

Li et al. [68] used three different male dies- stiff male die, an aluminium male die, and a nanoceramic powder male die to create micro-arrayed deep drawn parts from graphene oxide (GO)-reinforced NiCo (NiCo/GO) nanocomposite foil. According to their research, as the female die diameter of a male die containing nanoceramic particles decreases, the depth-diameter ratio increases. Additionally, larger ratios of depth to diameter and rates of thinning are caused by volume conservation. A minimum thinning rate of 3.79% was reported with diameters of female die as 400 µm and at depth to diameter ratio of 0.709. The micro-deep-drawn SS304 circular cups were the subject of a study by Luo et al. [54], which reported that roughness of surface, taking into account size effects, significantly affects the quality of product (evenness in thickness and accuracy of shape), drawability (minimum thickness achieved), and overall spring back.

Aminzahed et al. [65], [69] examined different micro-deep drawing operation scales for rectangular cups powered by a piezoelectric actuator. According to their experimental research, holder pressure and drawn radius can be disregarded in the micro-scale deep drawing process since they have less of an impact on punch force, spring back and thickness distributions than they do in the macro-deep drawing.

Guo et al. [70], investigated the influence of size effect on deformation behaviour and consequent development of defects during micro deep drawing process. They experimented with various thickness and sizes of grain to determine the properties of a micro deformed sheet. For the specific grain size, it was found that the deformation load rose with thickness and decreased with increasing particle size. Greater size of grain and reduced thickness size lead to earing. This investigation revealed a progressive rise in the produced cup's thickness, alongside wall, from bottom radius to edge of the cup.

According to Molotnikov et al.'s [44] research, the thickness of blank (t) to material grain size (D) ratio-controlled size effect. The research indicated the critical thickness to diameter ratio values below which the size effect becomes significant. Guo et al. [60] used crystal plasticity modelling to study the size-dependent earing evolution in micro-deep drawing of TWIP steel, taking into account the impact of the orientation of initial grain and geometrical sizes. According to the research, the workpiece of bigger size scaling factor had an earring profile that was more significant at the microscale than it was at the macroscale. Furthermore, the size scaling factor had a significant impact on the design of the earrings.

Even in cases when there is no change in the relationship between the primary geometrical features, the process behaviour is greatly influenced by the size of the portion. When constructing MDD, tribological size effects are to be taken into account because friction coefficients rise noticeably as process dimension decreases [71]. Material’s flow stress is affected by density, form, and microstructure type and size effect. According to reports, formability declines as grain size drops and with the increase in grain size to thickness ratio. Size effects affect the forming forces, spring back, dimensional accuracy, and shape accuracy of the parts.

3.3.2.2. Parametric Effect

For evaluating sheet material formability, forming limit curves, or forming limit diagrams (FLD) have been employed. A team of researchers examined the impact of geometry of tool, various sheet materials, radius of die and radius of tool geometry in making formability index analysis for MDD process. The researchers sufficiently investigated the grain size effect, micro-friction, lubrication, blank holder force, size of die cavity, geometry of tool, and gap between blank holder and die on MDD performance. Additionally, researchers investigated how hydraulic pressure affected micro hydro deep drawing (MHDD) wrinkles and earing. This section summarises the work done by the researchers on the parametric effect and constructing limit diagrams (FLD) during MDD.

FLD is acquired through the execution of a mechanical test. Prior to deformation, the workpiece is marked in circles. State of stress and flow behaviour of material are determined by measuring the ellipse dimensions formed, due to deformation, from the designated circles. It is employed in metal forming procedures to forecast when a blank would fracture. Calculated forming limitations, however, are dependent on the imperfection value.

A formability index was developed by Chen and Lin [72] for rectangular cups of stain less steel formed through deep drawing. According to findings from experiment, the radius of punch and the radius of die corner were the key process variables influencing deep drawing of SUS304 stainless steel rectangular cups' formability. Their research found that formability rose up to a certain die corner radius and subsequently declined as the radius of die corner increased. Huang et al. [73] discovered that LDR for square cup is 2.56, Limiting forming ratio for elliptical hole-flanging process was 1.46. In 2003, Chen et al. [74] completed the drawing of square cup sheets of AZ31-Mg alloy. According to their research, AZ31 sheets showed far better formability at temperatures as high as 200°C as they did at room temperature. In their investigation, they found that a consistent flow of material at corner, under punch profile postpones fracture for a greater punch radius.

During the T2 foil micro-U deep drawing, Wang et al. [75] reported increment in punch load with increase in the blank holder force and a reduction in radius of female die. Behrens et al. [76] also noted increment in punch force with increase of punch force and reduction in radius of punch corner. In contrast to the cylindrical portions, this impact was more noticeable while rectangular cups are deep drawn. The geometrical variation of forming tools in MDD has a major impact on the punch force as well. Forming limit of MDD of square cup at various punch arc radii is examined by

Yeh et al. [77]. Change in position of fracture and forming limit from corner of wall to bottom corner were reported. At most thin portion of deformed blank fracture is observed at the point of maximum strain crossing the fracture forming limit.

Luo et al. [78] looked into effect of gap between die and blank holder on MDD of cups of SUS304. This investigation revealed a very small gap between die and blank holder, accurate over all shape of outside surface and uniform wall thickness. It is felt that, for increasing the performance of MDD, further research needs to be done on multi objective optimisation of radius of die corner and gap size. According to Gong et al. [43], the micro-conical–cylindrical cups' rim wrinkles had a substantial impact on the blank holding force (BHF).

According to a study by Li et al. [79], the micro part's thinnest thickness is more susceptible to fracture due to the residual stress that is created. At bigger grain sizes, there was noticeable thinning at the punch corner and nonuniformity in thickness. The grain size at the micro part's bottom increased the surface roughness. Because of the ironing effect, it shrank at the cup's wall during the deformation stage. The material groups with smaller grain sizes were found to have larger pulling forces and lower residual forces. It was discovered that the grain size increased the likelihood of wrinkles [79].

Larger grain sizes and downscaled thicknesses were found decreasing drawing ratios and flow stresses. Due to increment in ratio of size of grain to thickness, the influence of grain size was more noticeable when the sheet thickness decreased [80]. Because of wear accumulation and thickness distribution, the original blank surface morphology also had a substantial impact on the precision of the micro-cup form [81].

Vollertsen and Luo [52], [55], [82] examined the influence of roughness of sheet metal surface, inhomogeneity of sheet material and pressure of fluid on MHDD process. Their research revealed that size effects and hydraulic pressure had an impact on the height and quantity of wrinkles. Employing higher hydraulic pressures enhances MHDD tool service life and drawing ratio. Their research made clear that the best hydraulic pressure for MHDD should be chosen after taking into account the geometry of MHDD tool, morphology of surface, and sheet metal properties. In addition, the drawn cups' surface finish was enhanced by the application of high pressure.

Using soft polyurethane rubber dies, attempts have been made to MDD microcylindrical cups with a reasonably high aspect ratio. The forming load and the micro-cups' shape were greatly impacted by the rubber's compressibility. Furthermore, forming load is affected by thickness of floating ring, the ring surface's inclination angle, and the starting gap value. The forming load was lowered by increasing ring surface's initial gap and angle of inclination [83], [84].

Distribution of wall thickness was also impacted by the sheet material's anisotropic tendency. It is advised to use a blank holder having smoother surface and an ideal starting gap to avoid increased cup thinning at the corner of shoulder and sidewall during metal forming of thin sheet [85]. It is reported that thinning of walls of the cup generated, during of stainless-steel cups through flexible deep drawing, depends considerably on initial foil thickness [86]. Reduction of thickness and reduction in punch load of forming with reduction in blank thickness was reported [59].

Enhancement of quality of drawn cups with significant reduction in wrinkling is possible by adjusting the annealing temperature. The impact of microstructural features on the formability tendency and quality cups made of SS304 was examined by Zhao et al [59]. According to their investigation, the SS304 foil as received had poor formability. The drawn cup exhibits significant wrinkling issues and nonuniform symmetry at annealing temperatures of 700 °C and between 950 and 1100 °C. According to their research, 900 and 950 °C are the ideal annealing temperatures for minimising wrinkling and enhancing the quality of drawn cups.

According to Sato et al. [49], [50], in case of deep drawing of SS304 it is possible to enhance tribological properties with reduction in wrinkling tendency by mere controlling hydraulic pressure. In micro deep drawing process, variation of punch force with parameters of tool geometry like diameter of punch, drawing die radius etc. are reported by Behrens and Vollertsen [87]. Behren conducted both experimental and numerical investigations. According to their research, the punch force's important characteristics are the punch diameter and the drawing gap. Punch or the drawing die radii, however, were found to have less of an impact on the punch force.

Lu et al. [88] opines that blank holder force and grain size of sheet greatly influences displacement and drawing tension. According to their research, the drawing stress decreased as the grain size increased. However, with increase in size of grain and force on blank holder the displacement and elongation rate increases. Advanced techniques for forecasting flaws like spring back, thinning, wrinkles, in the deep drawing process were examined by Takalkar and Babu [89].

According to their study, composite material/multi layered can be conveniently processed to manufacture complex structures through deep drawing process.

Researchers looked into the impact of altering the parameters of micro-U deep drawing process. The primary factors taken into account were surface quality, angle of the U portion, punch load, and thinning. Research has shown that as the die radius decreases, the punch load increases. Additionally, research has shown that when blank holding force increases, so does the load on punch and U portion angle. Additionally, thickness strain evolution and plastic anisotropic behaviour during micro deep drawing of foils made of phosphor bronze was studied by Shimizu et al. [90]. The significance of geometric anisotropy, including flaws and surface topographical orientation, was investigated through experiments on the varied tendency of deformation of ultra-thin rolled metallic foils.

3.3.2.3. Effect of Lubrication or Coating on Die and Punch

Friction, asperities on surface, heterogeneity of material, contact mode, all have a big impact on micro-sheet forming processes. One of the main issues with micro-forming is lubrication. Lubrication is still a difficult operation, especially in production of micro cups due to the size effects caused by friction. During MDD, due to increase in the ratio of open to shut lubrication pockets and the intensification of the coefficient of friction, choosing of right lubricant is essential. Various researchers experimented MDD with punches and dies covered with different lubricants and coatings. In MDD, punch and die surfaces are coated using a variety of coating materials and coating processes. The various lubricant types utilised during MDD are castor oil, petroleum jelly, polyethylene film, soybean oil, TiO_2 oil-based nano additives.

Gong et al. [91] carried out MDD of macrocups with castor oil lubricant and dies and blank holders coated with DLC film. Enhancement of LDR and significant reduction in drawing force were reported.

Wang et al. [92] employed polyethylene film and DLC film for minimising friction when performing MDD on pure gold foil to prepare a micro-cup with an inner diameter of 1.1 mm. Improvements like superior surface quality, maintaining accurate diameter and homogeneous thickness distribution coupled with reduction in punch load are reported, especially under high contact stress with better resistance to wear and adhesion with substrate. Nevertheless, under extreme high contact stress, the PE film cracked at the corner of female die leading to increase in punch load and wall thickness at the micro-cup's upside portion.

Tribological investigations on MDD process with various surface coatings namely- DLC, TiN, MoS_2 are carried out by Wang et al. [93]. Strong adherence with the substrate resulted in a friction coefficient and increased resistance to wear of DLC layer in higher strain/stress situations. Because of its lower friction coefficient, enhanced wear resistance, reduced force on punch, and increased LDR, DLC film is thought to be a superior option during MDD for mass production. Multi layered DLC film coats of die produces homogeneous thickness distribution and beneficial surface quality [40]. Especially DLC coating on forming tools work well under dry running condition of MDD. Hu et al. [94] found that a DLC film under dry conditions had a lower friction coefficient than an MDD using mineral oil lubricant, which subsequently reduces drawing force.

During the MDD of micro-conical–cylindrical cups, Yeh et al. [77] observed that in comparison to petroleum jelly, castor oil and dry friction, employing polyethylene (PE) film yields a better drawing ratio with reduction in drawing force. When BHF was less than 4.2 N, wrinkles were seen on the micro-cup's rim, and when BHF was greater than 5.6 N, cracks were seen at the micro-cup's bottom. Kamali et al. [95] reported encouraging results in deep drawing of alloy of Mg and Li with nano TiO_2 addition to lubricant. They observed 14.14% reduction in drawing force and 42.16% reduction in last stroke drawing force.

Nonetheless, a notable impact of concentration of nano additives to lubricant on a reduction in the drawing force was seen. According to Kamali et al. [96], the ideal mass fraction of nanoparticles for producing micro-cups with a significant decrease in drawing force is 1 weight percent addition of nano TiO2 to oil. During MDD of copper alloys, Gong et al. [97] discovered that PE film produced better results than castor and soybean oils in terms of lowering drawing force, raising LDR, and maintaining superior quality of surface.

For reasons related to the ecology and economy, researchers also tried lubricant free forming. To regulate friction forces and material flow, Mousavi et al. [98] investigated deep drawing of DC04 without any lubricant. The deep drawing tool surface's topology change offered a lot of promise for processing to move away from the use of lubricants that are harmful to the environment. Rolling of the blank or micro structuring the blank reduces effective area of contact between sheet and tool and thereby minimising the friction force. Flosky et al. [99] examined wear and durability of a combination of deep drawing tools and DLC-coated stainless steel blanking while MDD of 1 mm cylindrical cups was conducted using E-Cu58 foil of 0.05 mm thickness and Lubricmax- Edel C lubricant. Utilising a tool coated with DLC in MDD improves wear resistance and durability. The DLC coating delaminated as a result of increased strain and tension within the first 5000 strokes. High density of tool material and pores & dispersed carbides ranging in size up to 35 µm may be the cause of the delamination.

3.4. Challenges and Scope for Future Research in MDD

In deep drawing process, tiny radii of punch and die cause metal to typically fracture and rip. This is may be due to the high stress concentrations, reduced material flow and increased bending and unbending. When small radii are used, the stress concentration at the punch and die corners increases, increasing the likelihood that the metal would fracture. Small radii may also prevent the material from flowing smoothly, which results in localized thinning and raises the risk of fracture or tear. Significant bending and unbending of the metal occurs around the tiny radii, potentially resulting in work hardening and ultimately fracture [50], [51].

Using punch and die with larger radii lead to wrinkling at the flange and wall of micro cup. This may be due to interaction of forces and material flow during deep drawing causes wrinkling in the micro cup's wall and flange. Larger radii for the punch and die allow for less constrained material flow, which results in compressive stresses and wrinkles. During deep drawing, the flange of the blank experiences radial tensile stress and tangential compressive stress. The tangential compressive stress is primarily responsible for wrinkling. When the punch and die have larger radii, the material flow is smoother, reducing the radial tensile stress, but increasing the tangential compressive stress and causes wrinkling. Wrinkling occurs when the compressive tangential stress exceeds a critical value [50], [51]. This can be expressed as:

$$\sigma_\theta > \frac{E^1 t^2}{R^2} \tag{1}$$

Where E is Young's modulus, t is thickness and R is the punch or die.
Therefore, in the MDD process, the choice of punch and die radii must be made carefully.

Micro deep drawing of Advanced High Strength Steels (AHSS) is a major concern. This is due to inferior formability of AHSS-steel. For AHSS materials, the conventional technique of using forming limit diagrams to anticipate the fracture's occurrence is ineffective. Furthermore, in order to form low formability materials, larger forming loads are needed. These increased loads, strains, and impacts must be tolerated by the materials used in the punch and die. In these cases, wear of die and punch has considerable influence on maintaining dimensions of micro deep drawn part within the specified tolerances.

It's important to choose lubricant carefully and apply it in the right way to reduce the process temperature. In simulation studies of MDD, while considering effect of parameters, minimising of wrinkles at wall, top flange is difficult.

A possible micro-manufacturing technique for producing micro-metallic items in batches is micro-hydromechanical deep drawing, or MHDD. Nonetheless, it is necessary to determine the ideal hydraulic pressure by considering MHDD tool geometry, surface morphology, and material characteristics of the foil. Due to the scale effects of friction, lubrication is the main issue poses difficulty in fabrication of micro-cups.

Choosing of right lubricant is essential for MDD. The process performance of MDD was enhanced by the use of a lubricant with nano additives, resulting into a drawn cup with a superior surface polish and less drawing force. More research on nano-additive lubricants is necessary, though, as it must take into account the sort, size, shape, and concentration of particular nanoparticles as well as those combined with other types.

With the completion of rules and regulations that are more environmentally concerned, lubricant free forming is also becoming more popular. Attempts were also made to use coated and micro structured tools for a lubrication-free deep drawing. Research has shown that for lubricant-free deep drawing, micro-structuring of the tools or blank is preferable. Instead of using harmful lubricants to environment, it would be preferrable modifying surface topology of deep drawing tool resulting into various texture geometries that are filled with solid lubricants.

The majority of MDD procedures tried to use punch and die surfaces coated in MoS2, TiN, polyethylene film, and diamond-like carbon (DLC). Nonetheless, coatings are still evolving with new materials and in tandem with the most recent advancements in thin-film technology and coating deposition techniques. This paper identifies opportunities for more research on the MDD process using hybrid micro structured tools, single- and multi-layer coatings. In addition, investigations on friction force effects, maintenance and material flow of MDD can be attempted.

4. Conclusion

This paper brings out state of art methods of deep drawing process which includes, hydro mechanical deep drawing (HMDD), deep drawing with magnetic effect using MR fluids and micro deep drawing. These methods are evolved for making the products of high quality for various industrial applications. The conclusions of this study are, one of the widely used deep drawing process is HMDD. During this process, blank is deformed between punch and die to acquire punch geometry while punch moves against the fluid in pressure underneath the sheet. This method has been widely used for deep drawing of different metals and alloys including laminated aluminium/steel sheets.

During hydro forming process, contact pressure of flange and sealing limit can be enhanced by employing Magnetorheological (MR) fluid. This is possible by flexibly varying viscosity of MR fluid under external magnetic field. During the deep drawing of parts, forming ability and forming limit of the part geometry have enhanced proportionally. Higher hydraulic pressures in micro-hydromechanical deep drawing resulted in a higher drawing ratio and a longer service life for MHDD equipment. Nonetheless, through modifications to state of stress &strain, form of blank, and micro-frictional condition, hydraulic pressure had an impact on the drawn cup's earing and wrinkling. Henceforth characteristics of sheet material, geometry of HMDD tool are the important parameters to be taken in to account to determine ideal hydraulic pressure for MHDD.

One of the main issues and a difficult undertaking in micro-forming is lubrication, particularly in production of micro-cups. This is primarily due to size implications of friction. During MDD of ultra-thin sheets, rather than coating of petroleum jelly or castor oil, coatings of a film of poly ethylene, diamond like carbon film(DLC) on punch and die yielded superior quality of surface, reduction in punch load, better dimensional accuracy and more uniform thickness distribution.

Deep drawing at the optimum forming conditions with suitable forming environments not only minimize the defects and reduce the number of rejections of the formed parts in the industries also reduces the energy consumption during deep drawing processes addressing the two global issues SDG 9 and SDG 12.

Future research of deep drawing can be micro deep drawing and deep drawing at elevated temperatures as well as cryogenic temperatures or even combination of these two as hybrid method of deep drawing.

Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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