International Journal of Scientific and Research Publications, Volume 5, Issue 2, February 2015
ISSN 2250-3153

Study of Deep Drawing Process Parameters: A Review

Chandra Pal Singh*, Geeta Agnihotri**

* Research Scholar, Mechanical Engineering, MANIT BHOPAL
** Professor, Mechanical Engineering, MANIT BHOPAL

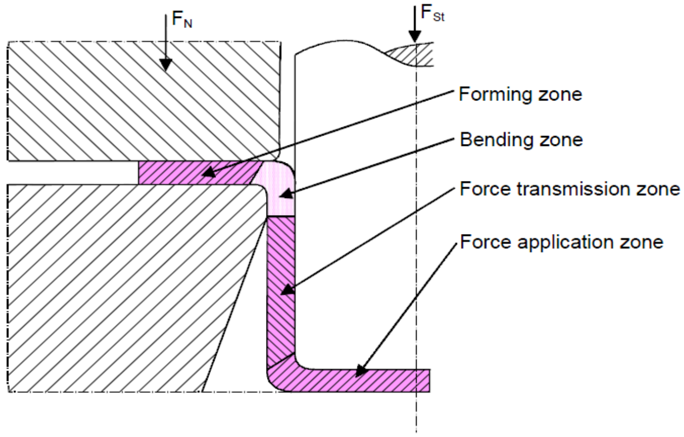
Abstract- Deep drawing process has been an important manufacturing process to produce automotive parts of good strength and light weight. There are many process parameters and other factors that affect product quality produced by deep drawing. This paper is highlighting recent research work and results in deep drawing. Deep-drawing operations are performed to produce a light weight, high strength, low density, and corrosion resistible product. These requirements will increase tendency of wrinkling and other failure defects in the product. Parameters like as blank-holder pressure, punch radius, die radius, material properties, and coefficient of friction affect deep drawing process. So a great knowledge of process is required to produce product with minimum defects. This review paper has given the attention to gather recent development and research work in the area of deep drawing.

Index Terms- Deep Drawing, Blank Holder Pressure, Blank Shape, Friction, Punch Force, Drawing ration, wrinkling

I. INTRODUCTION

Sheet-metal forming processes are technologically among the most important metalworking processes. Products made by sheet-forming process include a very large variety of different geometrical shapes and sizes, like simple bend to double curvatures even with deep recesses and very complex shapes. Typical examples are automobile bodies, aircraft panels, appliance bodies, kitchen utensils and beverage cans. Sheet-metal forming processes are widely used in the manufacturing industry. It is usually involved in developing and building tools namely die and punch. Usually, tools are costly and the cycle time for building them is long. However, once die and punch are built, the tools can be used to produce a large amount of products. Therefore, sheet-metal forming is a simple and efficient manufacturing process. Great productivity and low production cost can be expected for commercial scale production. As mentioned that the flat sheet of metal is formed into a 3-D product by deep drawing process. The basic tools of the deep drawing process are blank, punch, die and blank holder (or pressure plate). Deep drawing is affected by many factors such as material properties, tool geometry, lubrication etc. Because of these factors, some failures may occur during the process. Tearing, necking, wrinkling, earing and poor surface appearance are the main failure types that can be seen in deep drawing. Tearing and necking are caused by the tensile stresses and they are types of tensile instabilities. Another failure is wrinkling, caused by compressive stresses unlike to tearing and necking. When the radial drawing stress exceeds a certain value compressive stress in the circumferential direction becomes too high, so plastic buckling occurs. The four major defects which can occur during deep drawing are fracture, wrinkling, earing and spring back .The phenomenon of wrinkling (flange instability) is specific to the process of deep-drawing . Instability in the work piece, also
jectives are to obtain defect less or minimum defects in product.
ving operation. Because a part wrinkled during the deep drawing
factors affect the deep drawing process may be categorized into

iction, drawing ratio, material properties. Geometrical parameters
radii of cup. Machine parameters include die radius and punch
e stress-strain and anisotropy behaviour of the sheet metal to be
anisotropy behaviour in sheet metals, a proper knowledge of the
d.



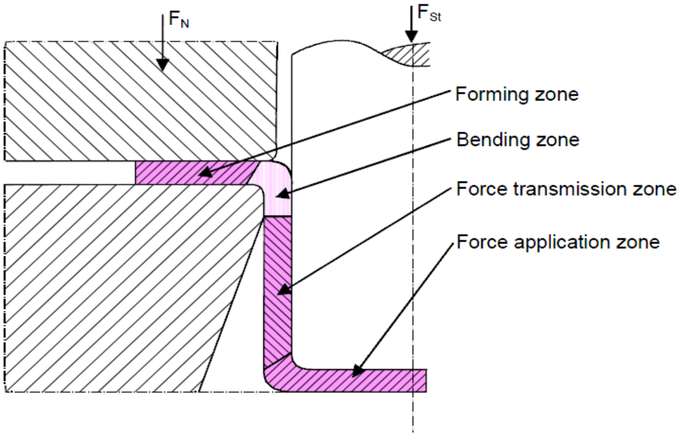


Fig 1: Stress zones in Deep Drawing

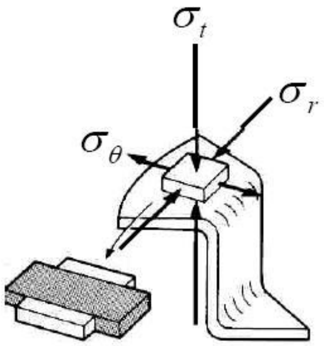


Fig 2: Stress Zone on Element

2. Literature Survey

Literature review has been categorized on the basis of the parameters which controll forming process, the quantities which decide successful execution of the process and the quality of the product. The important parameters and factors are:

(i) Blank holder force (BHF) and optimisation BHF.
(ii) Punch force and punch speed
(iii) Friction
(iv) Blank shape
(v) Forming Limits
(vi) Stress and Strain Distribution
(vii) Thickness variation
(viii) Wrinkling
(ix) Some other defects

2.1 Blank Holder Force (BHF) and Optimization BHF

Higher BHF is always desirable to eliminate wrinkling in deep drawn cup shaped product, but always there have been attempts made to predict a minimum BHF. A lot of research work has been reported to investigate the effect of BHF on product quality, material flow, strain path, stress distribution, thinning (at wall) and thickening (flange) of sheet metal, defects in product. Jaisingh et. al. (2004) has suggested that the blank holder force has the maximum effect on the thinning strain, the coefficient of fiction, plastic strain ratio. Also the strain-hardening exponent depends on BHF. Tommerup et. al. (2012) has investigated the effect of blank holder pressure on strain path in the sheet during forming process. A tooling system has been developed to investigate material flow, which is capable of controlling the distribution of blank holder pressure. This tooling system was integral to press and capable to run eight different pressure schemes. The tooling system consisting of a controller to regulate the process parameters, an actuator system to control BHF, a tool with embedded hydraulic cavities. The strain path has been checked by applying variations in the cavity pressures. In this research the drawing of rectangular specimen has been carried out. Van Tung Phan (2012) has simulated the deep drawing process for ferritic stainless steel and investigated the effect of variation of blank-holder pressure and friction on earing profiles. The simulation results compared with experimental data. Blank holding force and punch speed affect product quality and production rate. Manabe et. al. (2002) has proposed a new combination of punch speed and blank holder fuzzy control for deep drawing process. The control system consists of the fuzzy inference and the database. In this research the investigation of five variables like punch load, punch stroke, maximum apparent thickness (blank-holder displacement), SPD (punch speed) and blank reduction ratio have been recorded. The cup height improvement and the processing time reduction have been chosen as the object functions for evaluation fracture functions. It has been proven that the new combination of SPD and BHF fuzzy control system has improved performance with increased productivity with 25% forming time reduction. Wifi et al. (2007) has presented some aspects of blank-holder force (B.H.F.) schemes in deep drawing process based on finite element assessment. In all models, ABAQUS-Explicit general purpose finite element code has been used with full 3-D capabilities to account for anisotropy of sheet metal and wrinkling of the cups. The blank made of Al 5182 alloy has been used and assumed to be elastic-plastic. Friction has also been considered in simulation using an average overall simple Coulomb friction model with Coefficient of friction = 0.1 between the blank and the tool.

Gharib et. al. (2006) has developed an analytical model for the cup drawing process to calculate the induced stresses and strains over the deforming sheet at any stage of deformation until a full cup is formed. This model has been used as the solution engine for the optimization of the blank holder force for such cups avoiding failure by wrinkling or tearing. The analytical model has been established by considering plastic strains, principal stresses, and von Mises stresses. The results of the incremental analytical model for punch travel vs. punch force, and circumferential strain distributions show good correlation with the experimental results. The present model can be useful in conducting parametric studies on the different parameters which are affecting the process. Volk et. al. (2011) has simulated deep drawing process to investigate, optimized blank holder force (BHF) for an asymmetrical work piece from household appliances industry. In this research work the specific blank holder forces have been identified for minimum wrinkling and for the improve quality product. It has been suggested that the quality of a work piece can be improved with a better holding system. It is evident that even small changes in BHF can lead to failure during the process. These failures can be avoided if a variable BHF is applied, but the correct trajectories need to be chosen.

2.2 Punch Force and Punch Speed

Zhao et. al. (2007) has presented hydro-mechanical reverse deep drawing of cylindrical cups with axial pushing effect. The axial pushing force is exerted on the brim of the blank by a pushing ring, this reduces radial tensile stress at the sidewall and the risk of occurring fracture can be reduced considerably. The radial stress at punch-die zone increases with friction and bending, this reduces tangential stresses and thus reduces wrinkling. Also loading capacity of sidewall is enhanced due to strain hardening effect. The finite element simulation for hydro-mechanical reversed deep drawing process has been done successfully with DYNAFORM-PC code combining with modifying load mask keyword manually. The experimental results are in good agreement with the numerical simulation results. Saniee et. al. (2003) has investigated the required drawing force by different methods such as analytical, numerical and experimental techniques. FE simulation has been conducted to study the effect of element type on the forming load and the variation of the thickness strain. The influence of the friction coefficient on the drawing load has also been investigated and maximum drawing force has quantitatively been investigated for both the analytical and FE methods. Among different analytical relationships, Siebel’s formula provided the most accurate maximum drawing force for the process under consideration. Browne et.al. (2003) has considered punch and die geometry, blank- holding pressure, top-ram pressure, lubrication, and drawing speed in the deep drawing process and their effects has been studied on 9mm thick CRI steel cups. The optimum parameters for reduced punch loads have been investigated with lubrication by plastic on both sides. The optimum parameters to provide the least variation in wall thickness distribution has also been investigated i.e. optimum ram pressure blank-holding pressure and speed. Atrian Amir et. al. (2013) has investigated the effect of different parameters on deep drawing of laminated sheets. The experimental and finite element studies of the deep drawing process of steel/brass laminated sheets have been performed to show places of tearing for bimetal cup. A linear relation was obtained between the initial blank diameter and the maximum necessary force. Ouakdi et. al. (2012) has investigated the effect of holding force and die radius in a stretch bending test on spring-back. An experimental set up has been developed to find the effect of holding force and die radius on stretching depth. For evaluation, the drawn part has been divided into three critical regions or zones. First zone which is curved takes the shape of cylindrical stretching rod. Second zone subjected to thickness variation which is slightly curved due to residual stresses. Third zone is highly deformed by the stretching effort and bending due to the entrance curvature of the die. The results show that an increase in blank holder force reduces sliding of the sheet between the die and the blank holder and reduces spring-back by increasing the tension. It has also been observed that the greater the entrance radius of the die, the smaller the final spring-back and spring-back decreases in a non-linear fashion with stretching height. The evaluation of spring-back by the stretching height is in agreement with that by the angular orientation of the extremity. Kakandikar et. al. (2005) has used genetic algorithm to optimise the process and geometry parameters for mild steel cup. In this research failure limit diagrams have been plotted to study and compare the formability analysis of the geometries. Finite element analysis simulation software has been used for the validations of the results after optimization. The results have been analysed in the form of failure diagrams of original geometries with considered failure points and failure diagrams for optimise geometries with no failure points.

2.3 Friction

Friction is another important factor that influences deep drawing process. Surface quality of finished product, tool life and draw-ability of sheet are well dependent on presence of good lubricating film between contact surfaces. In metal forming processes friction influences the strain distribution at tool blank interface and drawability of metal sheet. Also drawability of metal sheet affects wear of tool. Yang (2010) has simulated the deep drawing process to analyze friction coefficient and strain distribution by combining an elastic-plastic FEM code with a friction model. Numerical results are in accordance with the experimental results for the film thickness and the strain distribution. Liu Qiqian et. al. (2012) has simulated micro multi point forming process with cushion. A finite element model with the effect of size has been developed to simulate micro multi point forming process. This research dealt with the effect of parameters like effect of cushion material, cushion thickness, coefficient of friction on the thickness variation and surface finish of the product. In this research results show non- uniform relative thickness distribution from centre to the edge in the deformed sheets. Also it has been found friction affects relative thickness distribution and surface quality in micro multi point forming process. Colgan Mark et. al. (2003) has studied influencing factors like the punch and die radii, the punch velocity, clamping force, friction and draw depth. Experimentally effect of various parameters has been observed then statistical analysis has been performed. The statistical treatment ANOVA has been applied to the results of the experiment to determine the percent contribution of each factor. Study of the ANOVA table for a given analysis helps to determine which of the factors need control and which do not. It has been observe that the punch/die radii have the greatest effect on the thickness of the deformed mild steel cups compared to blank-holder force or friction. It has been observed that smaller is the punch/die radii, greater is the punch force and shorter is the final draw. It has also been observed that if the blank-holder force is not kept within the upper and lower limit of reasonable range, it does have a significant effect on depth of draw. Also tearing of cup through the bottom may occur if the force is too high and if too low wrinkling of the flange area may be occurred. Allen et. al. (2008) has developed experimental set up to determine the effect of lubrication on expansion of die ring during deep drawing of axis-symmetric steel cup. An experimental set up was developed to record punch force and displacement, blank-holder force, and die hoop strain. Different oils were used to provide lubrication between blank and die. The surface finish and wall thickness of the cups produced during the experimental work were measured and evaluated to determine any correlation with the measured die expansion. FEA simulations have been developed for different lubrication conditions and tooling on the process. The experimental results based on die expansion under different lubrication conditions show a difference in the level of die hoop strain. This work also suggest that if lubricating oil film of definite thickness is provided in deep drawing, a expected surface finish could be obtained on final product. FEA models with lubricating oil film thickness can simulate deep drawing more realistic. Yang (2010) has presented elastic-plastic FEM code to simulate deep drawing process with friction model. Numerical analysis has been done to analyze the friction coefficient and the strain distribution in lubricated deep drawing. In this research work the surface roughness is taken into account by using Wilson and Marsault's average Reynolds equation that is appropriated for mixed lubrication with severe asperity contact. In this research the film thickness and strain distribution for various tribological parameters are predicted and compared with the experiment. Numerical results show that the present analysis is in accordance with the experiments for the film thickness and the strain distribution. It has been suggested that the larger value of full film lubrication region results in the more uniform strain distribution. This research work also suggested that when film thickness is greater than composite roughness by three times, the lubrication is full film condition and contact area ratio is almost zero, the contact area ratio near the outer edge of die is about zero and the friction stress is small. The largest value of contact area ratio occurred when the surface asperity of die and blank comes into contact, and it will result in the larger value of friction stress. Generally, lower friction results in a more uniform radial strain distribution. The larger value of full film lubrication region results in the larger value of the low-friction part and the lower value of peak's strain. Thus, an effective lubrication can prevent direct contact of the surface asperity, which enhances the draw-ability of deep drawing. Padmanabhan et. al. (2007) has presented the effect of process parameters such as die radius, blank holder force and friction coefficient on deep drawing of stainless steel. In this research FEM with taguchi technique has been used to determine the proportion of contribution of three important process parameters in the deep-drawing process. Taguchi method of experimental design was used to plan the numerical simulations. In Taguchi design, using two levels of each factors form screening experiments to determine a model of the system to a linear approximation. After designing experiments with various combinations of process parameter levels, FE simulations were carried out to predict the deformation behaviour of the blank sheet. The results obtained from the FE simulations were treated using statistical approach namely, ANOVA method. The purpose of using ANOVA was to find most influential parameters that govern the deep-drawing process that markedly influence the thickness distribution. The analysis of variance (ANOVA) was carried out to examine the influence of process parameters on the quality characteristics (thickness variation) of the circular cup and their percentage contribution. The die radius (89.2%) has major influence on the deep-drawing process, followed by friction coefficient (6.3%) and blank holder force (4.5%). Hol J. et. al (2012) has studied a friction model that can be used in large-scale FE simulations. The friction model includes two flattening mechanisms to determine the real area of contact at a microscopic level. The real area of contact is used to determine the influence of ploughing and adhesion effects between contacting asperities on the coefficient of friction. A statistical approach is adapted to translate the microscopic models to a macroscopic level. Results of the simulations have shown reasonable values for the coefficient of friction in the case of normal loading only, namely between 0.13 and 0.145. If flattening due to stretching is also incorporated, more realistic values are achieved (between 0.13 and 0.19). Karupannasamy (2012) has investigated deep drawing process for different lubrication conditions considering the micro-mechanisms. Instead of constant friction given by columns friction law, local coefficient of friction is considered to predict coefficient of friction more accurately. Zhenyu Hu (2011) has investigated the application of size dependent friction function into FEM to optimise shape of micro rectangular flange free parts. This research has been focused to investigate the application of friction model of circular parts for the deep drawing of rectangular parts. Topological effects i.e. effect of friction on size of parts to be drawn has also been investigated with simulated friction model. From this research it has been found that simulated friction model for circular parts are valid for rectangular deep drawn parts. Hassan et. al. (2003) has proposed friction aided deep drawing using eight segmented metal blank to improve the defects of Maslennikov process. In Maslennikov process, the elastomer is ring used as pressure medium, the ring is loaded through die to deform the blank material plastically. Maslennikov process has limitation due to small deformation resistance and short life of elastomer ring. The eight segments can move radially in and outward at different blank holder force at constant speed. Due to compressive nature at non slip point, the area of contact increased compared to Maslennikov process and fracture does not occurred. Cups of drawing ratio of 4.0 and height of 91 mm obtained successfully with new process. To investigate proposed deep drawing process experiments have been carried out using soft aluminium sheets of 0.5 and 1.0 mm in thickness. With the new proposed process drawability has increased as coefficient of friction increases. Hassan et. al. (2003) has introduced friction aided deep drawing process by segmented blank holder into four parts. The deformation has been obtained mainly by friction force between blank and blank holder i.e. at the flange. It has been observed that new process provides higher drawing ratio and it has overcome the short comings of Maslennikov's process. Cups with higher drawing ratio i.e. 3.8 and 5.5 have been produced with heights 48 mm and 75 mm respectively. It has been concluded that the process is suitable for low grade steel. Friction aided deep drawing process with segmented blank holder divided in four tapered segments has been investigated by Hassan et. al.(2005). In this study blank holder is having moving and stationary layers. The four moving segments capable of moving radially with uniform speed will have friction force with stationary part and this friction force is used to draw sheet metal. This study has concluded that parts can be produce efficiently with drawing ratio 3.76 with no localized wrinkling. Kim et. al. (2012) has studied coefficient of friction for non uniform pressure by conducting draw bend tests. Tested coefficients of friction are used in FE code for local contact conditions such as the sliding speed, contact pressure and sliding direction at the macroscopic level. Validation of the results has been done by the circular cup drawing experiments and simulations. In this research the contact pressure maps were developed from simulations, which has been included in the analysis of test data to measure the pressure dependency of friction coefficient. Hao et. al. (1999) has developed friction measurement apparatus for sheet metal forming. Friction tests conducted has shown that coefficient of friction increases with increasing test specimen strain, increases with increasing local contact pressure, decreases with increasing stretching speed, i.e. strain rate, and decreases with increasing pin radius. Kim et al (2007) has considered various factors such as punch force, blank holder force (BHF), draw-in length, perimeter of flange after test, change of surface roughness, and surface topography to evaluate the performance of different lubricants. In deep drawing friction is very important factor and flange area is most affected by friction. Due to severe friction there may be thinning or failure of the side wall in drawn cup at the flange area. According to Coulomb's law as the blank holder pressure increases, the frictional stress also increases, so therefore by determining the maximum applicable BHF without failure in the cup wall performance of lubricants may be evaluated. The coefficient of friction for each lubricant tested has determined through the FE-based inverse analysis by matching the predicted and measured values of the load-stroke curve and the draw-in length. Friction coefficients of the lubricants have been implemented in FE codes to get maximum punch force.

2.4 Blank Shape

To minimize the process defects and optimize the process, knowledge of the process and material variables are required. Blank shape is one of the important parameter in deep drawing process as the quality of deep drawn product, thickness distribution, forming limits, minimizing the defects can be improved by having optimum blank shape, also material cost of product reduced if proper blank shape is selected. Molotnikov et. al.(2012) has investigated the size effect on maximum load and limit drawing ratio for deep drawing of copper. Numerical analysis and experimental analysis have been done to study the effect of ratio of blank thickness to grain size on blank thickness. Through mathematical modelling and experimental work it has been suggested that size effect play an important role in deep drawing when grain size kept constant and dimensions of work-piece get reduced. This research has suggested the dislocation density based model to take into account for the effect of the specimen dimensions on its mechanical response. Dongkai Xu (2012) et.

al. has proposed a topology optimization method based on Solid Isotropic Microstructure with Penalty (SIMP) to reduce the weight of key die components. To optimize die structure local load mapping has been done which interact with SIMP-based topology optimization method. This gives an idea about forces acting on tooling faces as the blank holder force and different interaction forces affect blank holder structure and these forces will have effect on tooling or die components. In this research the blank holder weight is optimized i.e. blank holder is redesigned and machine through topology optimization, based on optimization results. Optimized blank holder is tested and stamping results are recorded. Results show that the blank holder weight is reduced by 28.1% and defect free stamping parts are formed, also the thickness difference between the original and newly stamped parts along a cross section is less than 0.06 mm, i.e. 4.29% of the initial blank thickness. Fazil et. al. (2012) has proposed iteration based algorithm to optimize blank shape. In the proposed algorithm the process modelled with initial blank shape. The required contours compared with contours obtained at the end of deformation. The deviation of the obtained contour from the required contour is measured and blank shape is modified using the blank optimization algorithm and process analyzed again. Repeatedly the process minimizes the deviation at every boundary node. In this proposed methodology the initial blank is optimized based on the shape error and the deformation path length of the boundary nodes. Talic et. al. (2009) has determined an optimum blank shape that has not caused earing. In this research the forming process has been simulated using Abacus CAE. Blank shape influences forming load, material requirement and possibility of defects. It has been concluded that optimum blank shape reduces forming load, increases forming limits and reduces possibilities of wrinkling and tearing. Lang et. al. (2009) has simulated hydro-forming process using LS-DYNA3D to determined optimized blank shape and the effect of punch pressure. The simulated results have been validated experimentally on a 550-ton double-action sheet hydro-forming press. Aluminium alloy 2B06 (China brand) has been used with thickness 1.5mm. The results show that, pressure curve is quit close to optimized one.

2.5 Forming Limits

LDR is the maximum drawing obtained in deep drawing process, it is limited by thickening at flange. The flange portion subjected to radial tensile load and circumferential compressive load. Circumferential load causes flange thickness to be increased. At cylindrical portion biaxial tensile loads act causing blank thinning of sheet. Similarly due to biaxial loading at sheet and tool interface causing a danger of fracture at the interface. BHF can control thickening at flange portion and thinning at blank – tool interface.

Forming limits are one of the important parameter in deep drawing and it is dependent on process parameters. Lot of works have been reported to find forming limits and forming curves. The forming limit of an HDD process is largely dependent on component shape. Kandil Anwar (2003) has presented experimental investigation to find the effect of hydro-forming deep drawing parameters on drawability of different metals. An experimental test rig has been developed to produce symmetric and non-symmetric cups. Wrinkling in case of hydro-forming is very severe failure as compared to conventional deep drawing. During the cup forming process failures occurred and these failures were eliminated by adjusting initial pressure. It has been found that the maximum pressure ranges between 0.15-0.3 of the mean flow stress of sheet metals. LDR has been determined by maximum blank size used to obtained successful drawn cup from each sheet metal. It has been found strain hardening coefficient affects LDR and higher LDRs has been obtained with hydroforming deep drawing as compared to conventional deep drawing due to more uniform strain hardening. Drawing ratio has been found to be the function of the initial pressure in pressure container and so initial pressure inside pressure container plays a significant role in hydro-forming process. Sokolovan et. al. (2012) has studied formability of layered composite. It has been observed that the forming behaviour of the three layered sandwiches is strongly influenced by the geometry of the punch and the core thickness. It has been observed that by increasing the total thickness of a material its resistance to deformation increases. The deep drawing force decreases with an increase of the sandwich core thickness from 0.2 to1.0 mm. It has been observed that increase in thickness of polymer layer increases inner metallic skin curve radius, this reduces the deformation. Also core thickness of polymer influences formability of metallic outer skins. As there is an increase in core thickness, metal draws easily. For the deep drawing with a circular punch the failure observed for sandwiches with core thicknesses between 0.2 and 1.6 mm in the cup head/edge region, whereas samples with a core thickness of 2.0 mm showed no failure by cracking. For all thickness combinations some wrinkling in the flange region of sandwiches has been observed. Ali (2012) has used analytical method for estimating the limiting drawing ratio (LDR) for drawing process and investigate the effect of drawing parameters such as coefficient of friction, strain hardening exponent, normal plastic anisotropy ratio, ratio of die arc to blank thickness and blank thickness to diameter on LDR. Banabic et.al. (2013) has experimentally determined the Forming Limit Curves (FLCs), representing the whole strain range specific to the sheet metal forming processes. Signorelli et. al. (2012) has investigated crystallographic texture effect on forming limit of an electro-galvanized steel sheet. Forming limit curves are representation of maximum strain as function of major and minor strain in the sheet plane that a material can sustain without failure. The anisotropy effect on the FLC has been evaluated using hourglass-type samples taken at 00, 450 and 900 with respect to the sheet rolling direction. In this research the influence of plastic anisotropy on FLD has been determined experimentally and numerically for a cold-rolled and annealed, electro-galvanized, DQ-type steel sheet. Predictions have been made with viscoplastic polycrystalline models. It has been concluded that the crystallographic texture of the zinc coating can affect the friction at the sheet-tool interface and, therefore, influences sheet-forming behaviour. Wu et. al. (2004) has simulated hydro-mechanical deep drawing of stepped components for determination of upper and lower forming limits using ABAQUS/ Explicit. FE simulation results are compared with reported experimental results. Comparison shows good agreement and it has been proposed, that FE analysis may be used to derive “master curves” of HDD. The results of FE simulations of the HDD of components with stepped geometries suggest that FE analysis may be used as an efficient tool to determine upper and low forming limits that refer, respectively, to the initiation of rapture and wrinkling of the sheet metal. Wan et. al. (2001) has determined limiting drawing coefficient for conical cups. The drawing coefficient for conical cups has been determined by mechanical analysis and combination of internal relation between cylindrical cup and conical cup. Results obtained from theoretical relations have been checked by experimental results. The limit deformation of conical cup drawing has been expressed by limiting drawing coefficient, the smaller is the limiting drawing coefficient the larger the limit deformation and vice-versa. This work also give equation to determine practical limiting drawing coefficient of conical cup and corresponding charts concerning forming limit curves and limiting drawing coefficient during first deep drawing. Thiruvarudchelvan et. al. (2007) has conducted experimental work for hydraulic-pressure assisted deep drawing process. The experimental test results have yielded data relating to pressure and blank holding force variations with punch stroke for drawing cups up to a draw ratio of 2.77. In hydraulic pressure assisted drawing process the drawing stresses are reduced by pushing effect of hydraulic pressure. In this research work it has been observed that if the counter hydraulic pressure is maintained at some optimum level, the full strength of the cup wall at the die throat can be utilized. Also increased pressure helps to take advantage of the increased flow stress of the strain-hardened cup-wall. Robert et. al. (2012) has proposed incremental deformation theory and compared it with the flow rule of plasticity. In both theories material non linearity has been taken into account by considering elasto- plastic formulation with anisotropic plasticity criterion. The process has been simulated using commercial FE code ABAQUS EXPLICIT. To test CPU time in both theories first a stretch forming of a spherical cup has been considered in which the contact conditions between the tools and the sheet are dominant and in second case the single point incremental forming of a cylindrical cup has been considered in which the localized contact zone between the tools and the sheet is following the tool path all along the forming operation. It has been observed that in first case CPU time reduced to 70% and in second case only 4% reduction achieved. It has been concluded that the new algorithm gives best result when the material non-linearities are dominant. Jayahari et. al. (2014) has investigated formability of austenitic stainless steel at higher temperatures. It has been observed that at higher temperature the limiting drawing has been increased and LDR up to 2.5 could be achieved. The improvement in LDR has been observed up to 3000C. It has also been observed that at warm conditions friction decreases and amount of residual stresses also get reduced which results in better quality of product. Al alloy has also been investigated and at warm condition Al alloy also showed improved drawability.

2.6 Stress and Strain Distribution

Assempour Ahmad et. al. (2011) has studied the effect of normal stress on hydrodynamic deep drawing process. Analytical model has been developed by considering classical theory of plasticity and geometrical relationships. In this study the influence of normal stress on the variation of blank thickness, stress and strain fields and punch force has been studied. The differences have been observed in thickness distribution, in stress and strain in both radial and circumferential direction and also in punch force with and without the normal stress. Higher thickness has been observed in the 2D stress state than in the 3D stress state. Also higher values of radial and circumferential strain have been observed in case of normal stress. This article suggests normal stress component should be considered in the deformation of HDD process to achieve accuracy in design. In deep drawing process strain path varies with variation in process parameters. To achieve successful deep drawing process, amount of strains and strain path has to be controlled. Thuillier et. al. (2010) has simulated deep drawing to predict the strain path change for the punch force. In this research Hill’s yield criterion has been used to perform three-dimensional numerical simulations of the process. Different hardening laws have been used to simulate process in different ways. In this research work evaluation of punch force has been done to predict change in strain path in redrawing. Strain hardening models take into account transient behaviours recorded during strain path changes. Jaisingh Amit et. al. (2004) has done sensitivity analysis of four parameters like strain hardening exponent, plastic strain ratio, coefficient of friction, blank holding force for deep drawing process on the basis of peak thinning strain developed as the main parameter. In this research plain strain analysis of bell shaped geometry has been done using Taguchi’s robust design technique. This research has investigated the effect of all the four parameter on the thinning of metal sheet. This research has suggested that the blank holding force has maximum effect on thinning strain. Other parameters i.e. coefficient of friction, plastic strain ratio, strain hardening exponent follows the blank holding force. Tabourot et. al. (2005) has investigated hardening curve (determined by image analysis) and strain localisation with FEM simulation for deep drawing of steel sheets. In this research the proposed numerical criterion of detection of the localisation of strain consists in counting the unloaded elements during numerical simulation from a post-processing program. This criterion applied to simulate a deep-drawing operation of an isotropic material. This enabled not only to give precisely the load applied to the tooling during the shaping operation but also to correctly determine the onset of the localisation within the part. Cwiekala , et, al. (2011) has proposed a method, which combines different analytical approaches to an accurate and fast deep drawing simulation. The developed simulation method is applicable to axisymmetric and prismatic deep drawing processes. Consideration of material behaviour, process parameters and deformation paths is possible in the proposed method. Due to the multistep simulation, even time dependent effects can be considered. The developed method gives a higher accuracy in calculating strain distributions than numerical one step solvers. A computation speed of the proposed method is 80 times faster for axisymmetric parts and for prismatic parts 20 times faster than numerical one step solvers. Besdo (2012) has studied a method for spring back phenomenon, which combines Taylor's and Sachs' theories of deformation. Taylor assumed that the deformation of all grains is uniform and Sachs assumed that the stresses are identical. Taylor's theory yields upper bounds for the inner power; Sachs' theory with its simplified statics leads to lower bounds. So combination of these two can produce good results. Spring back is very complicated phenomenon especially when the influence of bending processes is dominant. In such cases a bending and a subsequent re-bending process followed by a complete un-loading makes complicated material behaviour. The curvatures in bending and subsequent re-bending depend strongly on the elastic–plastic transitional behaviour. So therefore to study plastic deformation more descriptive material properties are required in elastic-plastic transition. Bagherzadeh et. al. (2012) has developed analytical models to investigate stress analysis and instability condition in hydro-mechanical deep drawing (HMDD) of cylindrical AL/St cups. These analytical models have been verified experimentally and could predict fluid pressure for HMDD process with reasonable accuracy. It has been observed that the critical fluid pressure is affected by layer thickness, drawing ratio and friction condition.

2.7 Thickness variation

In deep drawing the sheet metal thickness vary throughout the process. Thickness variation depends on process parameters. Several research works have been reported to evaluate thickness variation. Claudio et. al. (2006) has simulated deep drawing process for steel sheets to predict values of maximum punch force, in-plane principle deformation and thickness distribution in the sheet. The performance of model has been assessed by Erichsen test and the deep drawing of a cylindrical cup. Experimental validation of numerical prediction has been achieved for punch force, final value for the in-plane deformations and thickness distributions on the sheet. The model than has been applied to simulate industrial sheet metal forming process consisting of the deep drawing of a component of a commercial washing machine. Maximum punch force, in-plane deformation and thickness distribution predicted numerically have been in agreement with experimental values. Brabie et.al. (2013) has investigated the thickness variation in the case of micro/milli- cylindrical drawn cups made from sheets, called foils, having thicknesses from 0.05 to 0.20 mm. A mathematical model has been proposed based on experimental and numerical simulation results to control and minimise the thickness variation in the part wall where the variations of part diameter, wall inclination and wall curvature can generate negative effects. Natarajan et. al. (2002) has simulated deep drawing of circular blanks consider the axis-symmetric component using finite element techniques. A rigid plastic material model with the variation approaches are used in the finite element analysis. Amount of draw and flange thickness variation have been determined numerically and verified experimentally, for this the circumferential and radial strains have been calculated. Aluminium 1100-O grade material has been taken to analyse hemisphere cup drawing. Singh et. al. (2008) has investigated effect of process parameters on product surface finish and thickness variation in hydro-mechanical deep drawing process. In this research the effect of process parameters like pre- bulge pressure, cut off pressure and oil gap in hydro forming process are investigated. An Experimental set up has been developed for cylindrical cup drawing from flat circular blank by hydro-mechanical deep drawing process. The results have shown that pre-bulging pressure affected the cup quality in terms of thickness distribution and surface finish. It has been observed that there is a region where uniform thickness distribution and better quality surface obtained during drawing process. Also it has been observed that in hydro-mechanical deep drawing more uniform thickness obtained along the cup wall as compared to conventional deep drawing. Peled et. al. (2004) has used Cosserat theory of a generalized membrance to evaluate thickening of the blank including strain rate and strain hardening. The Cosserat theory of a generalized membrane has been used to obtain a transient nonlinear analytical solution for the rigid-plastic flow of the blank in a hydro-forming process. During the deep drawing process due to circumferential stresses there is always some thickening at the flange and to simulate deep drawing process this feature should be considered. The proposed analytical approach has the capability to calculate rate of thickening of the blank, the current radius, the current stress applied at blank holder and the current punch load. Thiruvarudchelvan et. al. (1998) has carried out theoretical analysis, finite element analysis and experimental work to determine correlation between the forming parameters of the process and to determine the mechanics of the process. The process has been simulated using the commercial FEM code MARC considering elastic-plastic behaviour. The Experimental work has been conducted using the tooling assembled on a 200 ton press. This investigation has suggested that the wall thickness is quite uniform except for the area near the punch nose radius when drawing cups at the three draw ratios 3.0, 3.3 and 3.5. This research suggests as drawing ratio increases thinning increases. Intarakumthornchai et. al. (2010) has studied the deep drawing process to minimise part thinning without crack and wrinkle. 2D interval halving and response surface methods have been used for the analysis of process parameters for hydro mechanical deep drawing of a parabolic cup. A nonlinear dynamic explicit code, LS-DYNA has been used for the analysis considering a friction coefficient of 0.12 between the blank and the punch. This research suggests that response surface method (RSM) could predict the optimal blank holder force and linear pressure profiles for hydro mechanical deep drawing of the parabolic cup. Dao et. al. (2011) has investigated effect of process parameters on thickness distribution of trapezoid cup. In this research, the optimum values of process parameters like punch speed, chamber pressure and coefficient of friction has been investigated using FEM and Taguchi method.

2.8 Wrinkling

Wrinkling is one of most severe defect in deep drawn product. Wrinkling may be defined as the formation of waves on the surface to minimise the compression stresses. There are two regions where wrinkling may take place first one is flange and second one is cup wall. Wrinkling on flange may be minimised by having optimum blank holder pressure but wrinkling on side walls cannot be prevented by any single parameters, so different parameters need to be set to minimise side wall wrinkling. Methods reported in literature to prevent side wrinkling are bifurcation method and energy method. In bifurcation method total wrinkling energy at the middle surface is taken as sum of bending energy, twisting energy, strain energy and work-done by in-plane stresses. Higher BHF is always desirable to eliminate wrinkling in deep drawing of cup shaped product, but always attempts have been made to predict a minimum BHF. Kadkhodayan et. al. (2011) has studied flange wrinkling in deep drawing process. In this research an analytical approach is used to study plastic wrinkling of flange in deep drawing by using bifurcation and Tresca yield criterion. The proposed analytical approach predicts more exact results for large width flange and explains effect of blank holder pressure on wrinkling. Morovvati et. al.(2010) has studied wrinkling phenomenon using theoretical, FE simulation, experimental methods for two layer sheets (aluminium-stainless). A 2D analytical model based on energy method has been developed for two layered sheet. In this model circumferential and radial stresses have been taken into account and thickness stresses has been ignored. This study shows the effect of parameters related to two-layer sheets such as lay-up and mechanical properties of each layer on wrinkling. The results suggested that for a given blank diameter, increase in punch diameter tends to decrease in the BHF and for a given punch diameter, increase in blank diameter decreases the BHF. The minimum required BHF to prevent wrinkling for A.I. lay-ups (when aluminium layer and punch are in contact) is higher than the one for S.I. lay-ups. It has also been observed that required forming load for A.I. lay-up is more than that required for S.I. lay-up. Abbasi et. al. (2012) has analyzed deep drawing of tailor welded blanks and analyzed wrinkling behaviour with thickness ratio greater than one. Experimental results in regard with conical cup wrinkling test are compared with analytical predictions based on bifurcation method. It has been observed that shear stresses are significant when thickness ration greater than one during wrinkling analysis. A good agreement of theoretical analysis and experimental analysis has been reached and it has been concluded that the wrinkling tendency of tailor welded blanks can be evaluated by bifurcation theory. Although a good agreement between the experimental and analytical results has been observed, but due to assumptions made for simplification there might be deviation between predicted results from experimental one. Hassan et. al. (2012) has investigated the effect of bulge shape and height on the wrinkling formation and sheet strength by using finite element method. The results show formation of concentric wrinkles pattern on thin flat sheets which improve part strength. En-zhi gao et. al. (2009) has investigated the effect of material parameters on deep drawing process, using thin-walled hemispheric surface part. A 3D-FE model has been developed for the deep drawing simulation of a thin-walled hemispheric surface part using finite-element code ABAQUS. It has been shown that, the maximum equivalent plastic strain occurs near the wall region outside the die radius. Wrinkle has been observed at this region and flange portion of the part. The results have suggested that, when elastic modulus increases but yield stresses decreases than maximum equivalent plastic strain occurs at wall region outside the die corners. And also when higher punch force occurs, elastic modulus or yield stress increases than yield stress more notable on punch force. These results provide some guidelines for selecting the materials of blank and determining the forming parameters according to the change of materials parameters. The experimental work was conducted on a 500 tonnes hydraulic press. Ayari et. al. (2009) has studied deep drawing process to evaluate the effect of parameters on wrinkling and thickness variations. In this research finite element simulations using ABAQUS/Explicit have been developed for two different material that are aluminium HFS and mild steel. It has been suggested that the coefficient of friction between different contact (Blank – Die, Punch Blank contact etc.) is the very important parameter. Malekani et. al. (2008) has investigated numerically and experimentally the die and blank holder shape to avoid wrinkling in deep drawing of cup. Finite element program code (ANSYS Inc., 2007) has been used to perform the numerical simulation of the deep drawing operation. In this research hoop stress distribution in the flange for different die and blank-holder has been studied for ISO 1624 low carbon steel with the thickness of 1.5mm. It has been observed that by increasing the slopes of die and blank holder up to an optimum amount, wrinkling can be minimised. The optimum amount of slope for die as 6.38 degree has been suggested. In this investigation it has also been observed that as the slope in die and blank holder increases LDR increases. Henriques et. al. (2009) has simulated sheet metal forming process using FEM codes ABAQUS/Standard to determine the description of wrinkling initiation and propagation during sheet metal forming operations. In this study distinct numerical simulation strategies, based on the Finite Element Method (FEM), have been used for the study of wrinkling initiation and propagation during sheet metal forming operations. Reddy et. al. (2012) has investigated dependency of wrinkling on various parameters like BHF, punch radius, die edge radius, and coefficient of friction in deep drawing process of cylindrical cup. As the wrinkling initiation and growth analysis has been difficult because of wide scattering data for small deviations, but this investigation has suggested some guide lines to minimise wrinkling. It has been concluded that increased blank holding force, reduce friction, large radius at tool edge and reduce deep drawing depth could minimise wrinkling.

2.9 Other Defects

Nanu et. al. (2012) has proposed a function that relates springback with process parameters and stress distribution in the sheet metal in the case of U stretch-bending. The proposed model has expressed stress distribution in the sheet as a function of process parameters, tools geometry and material properties, while the springback parameters as a function of stress distribution in the sheet thickness. Based on mathematical model the prediction of springback has been done in deep drawing process. Pereira Michael et. al. (2013) has studies experimentally sheet metal stamping process to examine the wear location, its type and severity that occurs over the die radius. In This research it has been suggested that the wear over the die radius primarily consisted of a combination of ploughing and galling mechanisms. Further it has been suggested that the galling wear mechanism, result in failure of the sheet metal stamping process that takes place over most of the die radius surface, therefore, it is critical to the overall tool wear response. This study has suggested that the overall tool wear response and tool life for the channel forming process is primarily dependent on the transient contact and deformation conditions experienced at the die radius and blank surfaces. Saxena et. al. (2012) has investigated damage behaviour to predict fracture initiation in deep drawing. In this research a parametric study has been proposed to investigate the effect of material, geometric and other process parameters on maximum cup height and to evaluate damage. The damage has been evaluated using the damage growth law proposed by Lemaitre and it has been suggested that Lemaitre model can predict fracture in deep drawing. In this research it has been suggested that the maximum cup height (i.e., the cup height at which the fracture initiates) increases with the sheet thickness, the die profile radius and the punch profile radius. In this study it has been observed that the plastic properties of material affect fracture initiation. In case of square cup fracture initiation is influenced mostly by the plastic deformation in the corner regions and less by the triaxiality. Lou et. al. (2012) has investigated fracture mechanisms to determine fracture forming limits. In this research a new criterion has been proposed considering damage accumulation induced by nucleation, growth and shear coalescence of voids. The equivalent plastic strain, the stress triaxiality, and the normalized maximal shear stress have been taken as function of nucleation, growth and shear coalescence of void to represent a fracture model. In this research fracture forming limit diagram has been suggested for dual phase steel sheets. The fracture model suggested in this research can predict ductile fracture in a stress triaxiality ranging from -1/3 to 2/3. Khelifa et. al. (2008) has presented a model based on anisotropic elasto-plastic and isotropic ductile damage for the prediction of damage in work-piece during stamping or forming of square cup of steel. In this research a coupled approaches have been suggested in which the damage evolution equation is directly incorporated and coupled with the constitutive equations. The results obtained from numerical simulation have been compared with experimental results. The proposed model also predicts the elastic, plastic, and hardening behaviours. Salehinia et. al. (2009) has simulated deep drawing using FE standard code ANSYS 9.0 considering the elasto-plastic behaviour for the blank to predict the relative wear depth. It has been observed that as planner anisotropy does not remain constant the relative wear depth in circumferential direction also changes on the die shoulder. Large anisotropic coefficient is in circumferential direction so less relative wear depth is in circumferential direction. In case of normal anisotropy relative wear depth is constant in circumferential direction. Also it has been observed that as the normal anisotropy index is higher the relative wear on the die shoulder will be higher. Increasing the radius of the die shoulder causes the relative wear depth to be decreased. Ali et. al. (2008) has studied deep drawing process to identify the region of punch stroke within which tear occur. In case of light weight components of complex shapes made of blank material which shows a small operating window, identification of critical tearing region enabled to develop strategy to produce sound parts. This study shows that if blank holder force is applied at an ultra- low frequency and synchronized with the punch force then BHF can be maintained within the process limits for the entire critical width of the critical tearing window and complex shapes may be produced. This research describes experimental investigations in which cylindrical-shaped cups are drawn with a pulsed blank-holder force (PBHF) at ultra-low (less than 1 Hz) and low (1–10 Hz) frequencies. The tests have been conducted with blanks of steel and of aluminium over a range of draw ratios. Tests have been conducted with different blank diameters in the range of 220–250 mm, with frequencies, in the range of 1–10 Hz and amplitudes between 10 and 50 kN.

3. Conclusion

This paper has critically reviewed the process parameters and their effect such as blank holding forces, die pressure, punch pressure, effects of friction etc. In this review about eighty two research papers have been critically reviewed for the study of all affecting process parameters. Blank holder force is one of the important process parameter that needed to be selected very carefully during deep drawing process. Blank holder force controls metal flow, it also affects thickness variation, strain path, stress path and wrinkling behaviour. Strain path is well affected by blank holder pressure. By maintaining an optimum blank holder pressure, precise thickness variation in drawn cup and strain path can be maintained. Blank holding force and punch speed affects product quality and production rate. Blank holder force also controls wrinkling. Blank shape is an important parameter in deep drawing process as the quality of deep drawn product. Blank shape influences forming load, material requirement and possibility of defects. It has been concluded that optimum blank shape reduces forming load, increases forming limits and reduces possibilities of wrinkling and tearing. Forming limits depends on various process parameters such as friction between blank and blank holder. Higher LDRs can be obtained with uniform strain hardening. FE analysis may be used as an efficient tool to determine upper and low forming limits that refer respectively to the initiation of rapture and wrinkling of the sheet metal. Friction is one of the most influential parameter in deep drawing process. Friction affects relative thickness distribution and surface quality in micro multi point forming process. The punch/die radii have the greatest effect on the thickness of the deformed material. If lubricating oil film of definite thickness is provided in deep drawing an expected surface finish could be obtained on final product. An effective lubrication can prevent direct contact of the surface asperity, which enhances the draw-ability of deep drawing. Drawability of metal sheet increases as coefficient of friction increases. Coefficient of friction increases with increasing test specimen strain, increases with increasing local contact pressure, decreases with increasing stretching speed, i.e. strain rate, and decreases with increasing pin radius. In deep drawing process strain path varies with variation in process parameters. To achieve successful deep drawn product, strains and strain path has to be controlled. By considering normal stress component in simulation of deep drawing process more accurate results can be obtained. The blank holding force has maximum effect on thinning strain. Due to blank holder force there will also be thickening of sheet metal at flange. Thickness variation at wall inclination and wall curvature has been very critical. The wall thickness does remain uniform for the area near the punch nose radius and the thinning increases as the draw ratio increases. Wrinkling is one of most severe defect in deep drawing process. By increasing the slopes of die and blank holder up to an optimum amount, wrinkling can be minimized. Increased blank holding force, reduce friction, large radius at tool edge and reduce deep drawing depth could minimize wrinkling. So for successful execution of deep drawing manufacturing process, a deep knowledge of all factors affecting the process is must.

REFERENCES

1. Abbasi M., Ketabchi M., Labudde T., Prahl U. , Bleck W. “New Attempt to Wrinkling Behavior Analysis of Tailor Welded Blanks During the Deep Drawing Process” Materials and Design, vol.40, pp 407-414, 2012.
2. Abdalla S. Wifi, Tamer F. Abdelmaguid, Ahmed I. El-Ghandour, “A Review of the Optimization Techniques Applied to the Deep Drawing Process”, vol., pp. 1111-1121, 2007.
3. Aboutalebi Farhad Haji, Farzin Mahmoud, Mashayekhi Mohammad, "Numerical Predictions and Experimental Validations of Ductile Damage Evolution in Sheet Metal Forming Processes", Acta Mechanica Solida Sinica Published by AMSS Press, Wuhan, China vol. 25, pp 648- 654 , 2012.
4. Ali S., Hinduja S., Atkinson J., Bolt P., Werkhoven R., “The Effect of Ultra-Low Frequency Pulsations on Tearing During Deep Drawing of Cylindrical Cups” International Journal of Machine Tools & Manufacture, vol. 48, pp 558-564, 2008.
5. Allen S.J., Mahdavian S.M. “The Effect of Lubrication on Die Expansion During the Deep Drawing of Axisymmetrical Steel Cups”, Journal of Materials Processing Technology, vol.199, pp 102-107, 2008.
6. Assempour Ahmad, Taghipour Ehsan, “The Effect of Normal Stress on Hydrodynamic Mechanical Deep Drawing” International Journal of Mechanical Sciences, vol.53, pp 407-416, 2011.
7. Atrian Amir, Saniee Faramarz Fereshteh, “Deep Drawing Process of Steel/Brass Laminated Sheets Composites” : Part B, vol. 47, pp 75-81 2013.
8. Ayari F., Lazghab T., Bayraktar E., “Parametric Finite Element Analysis of Square Cup Deep Drawing”, Archives of Computational Materials Science and Surface Engineering, vol.1, Issue No. 2, pp. 106-111, 2009.
9. Bagherzadeh S., Mollaei-Dariani B., Malekzadeh K. “Theoretical Study on Hydro-Mechanical Deep Drawing Process of Bimetallic Sheets and Experimental Observations” Journal of Materials Processing Technology, vol. 212, pp 1840-1849, 2012.
10. Banabic D., Lazarescu L., Paraianu L., Ciobanu I., Nicodim I., Comsa D.S., "Development of a New Procedure for the Experimental Determination of the Forming Limit Curves" CIRP Annals - Manufacturing Technology, vol. 24, pp 45-52, 2013.

11. Baosheng Liu , Lihui Lang, Yuansong Zeng, Jianguoc Lin, "Forming Characteristic of Sheet Hydroforming Under the Influence of Through-Thickness Normal Stress", Journal of Material Processing Technology, vol. 212, pp 1875-1884, 2012.
12. Besdo D. "Material Laws Denoting the Influence of Textures Due to Spring Back Simulations", Computational Materials Science, vol.52, pp 82-89, 2012.
13. Brabie G., Costache E.M., Nanu N., Chirita Vasile Alecsandri B., "Prediction and Minimisation of Sheet Thickness Variation During Deep Drawing of Micro/Milli Parts", International Journal of Mechanical Sciences, vol.68, pp 277-290, 2013.
14. Browne M.T., Hillery M.T. "Optimising the Variables When Deep-Drawing C.R.1 Cups", Journal of Materials Processing Technology, vol. 136, pp 64-71, 2003.
15. Cafuta G., Mole N., Stok B., "An Enhanced Displacement Adjustment Method: Spring-Back and Thinning Compensation", Journal Material and Design, vol. 40, pp 476-487, 2012.
16. Chiles V., Black S.C., Lissaman A.J., Martin S.J., "Principles of Engineering Manufacturing", Third Edition, ISSBN: 9780080539614, pp 183, 2002.
17. Colgan Mark, Monaghan John, "Deep Drawing Process: Analysis and Experiment", Journal of Materials Processing Technology, vol. 132, pp 35-41, 2003.
18. Claudio Garcia, Diego Celentano, Flores Fernando, Ponthot Jean-Philippe, Oliva Omar, "Numerical Modelling and Experimental Validation of Steel Deep Drawing Processes Part – II Application" Journal of Material Processing Technology, vol. 172 pp. 461-471, 2006.
19. Cwiekala T., Brosius A., Tekkaya A.E. "Accurate Deep Drawing Simulation by Combining Analytical Approaches, " International Journal of Mechanical Sciences, vol.53, pp 374-386, 2011.
20. Dao Thanh-Phong, Huang Shyh-Chour, "Study on Optimization of Process Parameters for Hydro-Mechanical Deep Drawing of Trapezoid Cup", Journal of Engineering Technology and Education, vol. 8, Issue No.1, pp. 53-71, 2011.
21. Delameziere Roberta A., Santo P. Dal, Batoz J.L., "Comparison Between Incremental Deformation Theory and Flow Rule to Simulate Sheet-Metal Forming Processes", Journal of Materials Processing Technology, vol. 212 pp 1123-1131, 2012.
22. DeSouza T., Rolfe B.F., "Understanding Robustness of Spring-Back in High Strength Steels", International Journal of Mechanical Science, vol. 68, pp 236- 245,2013.
23. En-zhi Gao, Hong-wei Li, Hong-chaoKou, Hui Chang, Jin-shan Li, Lian Zhou, "Influences of Material Parameters on Deep Drawing of Thin-walled Hemispheric Surface Part", Trans. Nonferrous Met. Soc. China, vol. 19, pp 433-437, 2009.
24. Faris Saad Theeyab, Shihab Suha Karim, "Study and Design the Hydrodynamic Deep Drawing Process for Blanks of Non Uniform Thickness", Diyala Journal of Engineering Sciences, Special Issue, pp 40-56, 2010.
25. Gantar G., Kuzman K. and Filipic B., "Increasing the Stability of The Deep Drawing Process by Simulation-Based Optimization", Achievements of Mechanical and Materials Engineering, vol.49, pp 243-246, 2005.
26. Gharib H., Wifi A.S., Younan M., Nassef A., "An Analytical Incremental Model for the Analysis of the Cup Drawing", Journal of Achievements in Materials and Manufacturing Engineering, vol. 17, pp 245-248, 2006.
27. Gharib H., Wifi A.S., Younan M., Nassef A., "Optimization of the Blank Holder Force in Cup Drawing", Journal of Achievements in Materials and Manufacturing Engineering, vol. No. 18, Issue No. 1-2, pp 291-294, 2006.
28. Grobmann K. , Penter L., Hardtmann A., Weber J., Lohse H., "FEA of Deep Drawing with Dynamic Interactions Between Die Cushion and Process Enables Realistic Blank Holder Force Predictions", Sciverse Science Direct vol. 12, pp 273-278, 2012.
29. Hao S., Klamecki B.E., Ramalingam S., "Friction Measurement Apparatus for Sheet Metal Forming", Wear (Elsevier), vol. 224, pp 1-7, 1999.
30. Hassan M.A., Takakura N., Yamaguchi K. "Friction Aided Deep Drawing Using Newly Developed Blank-Holder Divided into Eight Segments", International Journal of Machine Tools & Manufacture, vol.43, pp 637-646, 2003
31. Hassan M.A., Takakura N., Yamaguchi K., "A Novel Technique of Friction Aided Deep Drawing Using a Blank-Holder Divided into Four Segments", Journal of Materials Processing Technology Vol.139, pp 408–413, 2003.
32. Hassan M.A., Suenaga R., Takakura N., Yamaguchi K., "A Novel Process on Friction Aided Deep Drawing Using Tapered Blank Holder Divided into Four Segments", Journal of Materials Processing Technology Vol. 159, pp 418–425, 2005.

33. Hassan M.A., Saleh M.A.E. , Takakura N. , Ramesh S., Purbolaksono J. "Effect of Bulge Shape on Wrinkling Formation and Strength of Stainless Steel Thin Sheet", Journal of Material and Design, vol. 42 pp 37-45, 2012.
34. Henriques Marisa P., de Sousa Ricardo J. Alves, Valente Robertt A. F., “Numerical Simulation of Wrinkling Deformation in Sheet Metal Forming”, Portuguese Science and Technology Foundation, pp 1-12, 2009.
35. Hol J., Cid Alfaro M.V., De Rooij M.B., Meinders T., “Advanced Friction Modeling for Sheet Metal Forming”, Wear (Elsevier), vol.286-287, pp 66-78, 2012.
36. Hu Zhenyu “Realisation and Application of Size Dependent FEM-Simulation for Deep Drawing of Rectangular Work Pieces”, CIRP Journal of Manufacturing Science and Technology, vol.4, pp 90-95, 2011.
37. Intarakumthornchai Thanasan, Jirathearanat Suwat, Thongprasert Sirichan, Dechaumphai Pramote, “FEA Based Optimization of Blank Holder Force and Pressure for Hydro mechanical Deep Drawing of Parabolic Cup Using 2-D Interval Halving & RSM Methods”, Engineering Journal, vol. 14, Issue No. 2, pp. 15-32, 2010.
38. Jaisingh Amit, Narasimhan K., Date P.P., Maiti S.K., Singh U.P. “Sensitivity Analysis of a Deep Drawing Process for Miniaturised Products”, Journal of Material Processing Technology, vol. 147, pp 321-327, 2004.
39. Jayahari Lade, Sasidhar P.V., Prudvi Reddy P., BaluNaik B., Gupta A.K., Singh Swadesh Kumar, “Formability Studies of ASS 304 and Evaluation of Friction for Al in Deep Drawing Setup at Elevated Temperatures Using LS-DYNA”, Journal of King Saud University – Engineering Sciences Vol.26, pp 21–31, 2014.
40. Jun-chao LI, Chong LI, Tong-gui Zhou, "Thickness Distribution and Mechanical Property of Sheet Metal Incremental Forming Based on Numerical Simulation" , Elsevier Science Press Science Direct, vol. 22, pp 54-60, 2012.
41. Kadkhodayan M., Moayyedian F. “Analytical Elastic–Plastic Study on Flange Wrinkling in Deep Drawing Process” Scientia Iranica, vol.18, pp 250-260, 2011.
42. Kakandikar G.M., Nandedkar V.M., “Optimization of Forming Load and Variables in Deep Drawing Process for Automotive Cup Using Genetic Algorithm”, pp 1-10, 2005.
43. Kandil Anwar “An Experimental Study of Hydroforming Deep Drawing”, Journal of Material Processing Technology, vol.134, pp 70-80, 2003
44. Karupannasamy D.K., Hol J., deRooij M.B., Meinders T., Schipper D.J. “Modelling Mixed Lubrication for Deep Drawing Processes” Wear (Elsevier), vol. 294-295, pp.296-304, 2012.
45. Khelifa M., Oudjene M. “Numerical Damage Prediction in Deep Drawing of Sheet Metels”, Journal of Material Processing Technology, vol. 200, pp 71-76 2008.
46. Kim Hyunok, Sung Ji Hyun, Sivakumar Rajesh, Altan Taylan, “Evaluation of Stamping Lubricants Using the Deep Drawing Test”, International Journal of Machine Tools & Manufacture, vol. 47, pp 2120-2132, 2007.
47. Kim Y.S., Jain M.K. , Metzger D.R "Determination of Pressure Dependent Friction Coefficient From Draw Bend Test and its Application to Cup Drawing", International Journal of Machine Tools and Manufacture, vol 56, pp 69-78, 2012.
48. Lang Lihui, Li Tao, An Dongyang, Chi Cailou, Nielsen Karl Brian, Danckert Joachim, “Investigation into Hydro Mechanical Deep Drawing of Aluminum Alloy—Complicated Components in Aircraft Manufacturing”, Materials Science and Engineering A, vol. 499, pp 320–324, 2009.
49. Liu Qiqian, Lu Cheng, Fu Wenzhi, Tieu Kiet, Li Mingzhe, Gong Xuepeng “Optimization of Cushion Conditions in Micro Multi-Point Sheet Forming” Journal of Material Processing Technology, vol.212, pp 672-677, 2012.
50. Lou Yanshan, Huh Hoon, Lim Sungjun, Pack Keunhwan, “New Ductile Fracture Criterion for Prediction of Fracture Forming Limit Diagrams of Sheet Metals”, International Journal of Solids and Structures, vol. 49, pp 3605-3615, 2012.
51. Magar Susheel Madhavrao, Khir Mohan Yashwant, “Deep Drawing of Cup Shaped Steel Component: Finite Element Analysis and Experimental Validation”, International Journal on Emerging Technologies, vol.1, Issue No. 2, pp 68-72, 2010.
52. Malekani J., Pour Mostafa A., Eskandarzade M. and Totonchi Abolfazl, “Numerical and Experimental Investigation on Die and Blank Holder shape in Deep Drawing Process”, Journal of Applied Sciences, vol.8, Issue No. 11, pp 2153 – 2157, 2008.
53. Manabe Kenichi, Koyama Hiroshi, Yoshihara Shoichiro, Yagami Tetsuya “Development of a Combination Punch Speed and Blank-Holder Fuzzy Control System for the Deep-Drawing Process”, Journal of Material Processing Technology, vol.125-126, pp 440-445, 2002.

54. Molotnikov A., Lapovok R., Gu C.F., Davies C.H.J. Davies, Estrin Y., "Size Effects in Micro Cup Drawing", Material Science and Engineering, vol. 550, pp 312- 319, 2012.
55. Morovvati M.R., Mollaei-Dariani B., Asadian-Ardakani M.H. "A Theoretical Numerical and Experimental Investigation of Plastic Wrinkling of Circular Two Layer Sheet Metal in the Deep Drawing", Journal of Materials Processing Technology, vol. 210 pp 1738-1747, 2010.
56. Nanu N., Brabie G. "Analytical Model for Prediction of Spring Back Parameters in the Case of U Stretch– Bending Process as a Function of Stresses Distribution in the Sheet Thickness", International Journal of Mechanical Sciences, vol. 64, pp 11- 21 2012.
57. Natarajan S., Venkataswamy S., Bagavathiperumal P. "A Note on Deep Drawing Process: Numerical Simulation and Experimental Validation" Journal of Materials Processing Technology, vol. 127, pp 64-67, 2002.
58. Ouakdi E.H., Louahdi R., Khirani D. , Tabourot L., "Evaluation of Spring Back Under the Effect of Holding Force and Die Radius in a Stretch Bending Test", Materials and Design, vol. 35, pp 106-112, 2012.
59. Padmanabhan R., Oliveira M.C., Alves J.L., Menezes L.F. "Influence of Process Parameters on the Deep Drawing of Stainless Steel", Finite Elements in Analysis and Design, vol.43 pp 1062 – 1067, 2007.
60. Peled A., Rubin M.B., Tirosh J. "Analysis of Blank Thickening in Deep Drawing Processes Using the Theory of a Cosserat Generalized Membrane", Journal of the Mechanics and Physics of Solids, vol.52, pp 317-340, 2004.
61. Pereira Michael P. , Weiss Matthias, Rolfe Bernard F., Hilditch Tim B. "The Effect of the Die Radius Profile Accuracy on Wear in Sheet Metal Stamping", International Journal of Machine Manufacturing, vol. 66, pp 44-53, 2013.
62. Reddy R. Venkat, Reddy T.A. Janardhan, Reddy G.C.M., "Effect of Various Parameters on the Wrinkling In Deep Drawing Cylindrical Cups" International Journal of Engineering Trends and Technology vol.3, Issue No. 1, pp 53- 58, 2012.
63. Robert C., Delameziere A., Dal Santo P., Batoz J.L. "Comparison between Incremental Deformation Theory and Flow Rule to Simulate Sheet-Metal Forming Processes", Journal of Material Processing Technology, vol. 212, pp 1123–113, 2012.
64. Salehinia I., Shahani A.R. "Effect of Sheet Anisotropy on the Wear in Deep-Drawing Process of a Cylindrical Cup", International Journal of Mechanical Sciences, vol. 21, pp 856-868, 2009.
65. Saniee F. Fereshteh, Montazeran M.H., "A Comparative Estimation of the Forming Load in the Deep Drawing Process", Journal of Materials Processing Technology, vol. 140, pp 555–561, 2003.
66. Saxena Ravindra K., Dixit P.M. "Numerical Analysis of Damage for Prediction of Fracture Initiation in Deep Drawing", Finite Element Analysis and Design, vol. 47, pp 1104-1117, 2012.
67. Signorelli J.W., Serenelli M.J., Bertinetti M.A., "Experimental and Numerical Study of the Role of Crystallographic Texture on the Formability of an Electro-Galvanized Steel Sheet", Journal of Materials Processing Technology, vol. 212 ,pp 1367– 1376, 2012.
68. Sokolova O.A., Kuhn M., Palkowski H., "Deep Drawing Properties of Lightweight Steel/Polymer/Steel Sandwich Composites", Archive of Civil and Mechanical Engineering, vol. 12, pp 105-112, 2012.
69. Tabourot L., Vacher P., Coudert T., Toussaint F., Arrieux R., "Numerical Determination of Strain Localization During Finite Element Simulation of Deep Drawing Operation", Journal Material Processing Technology, vol.159, pp 152-158 2005.
70. Talic Amra, Suad Hasanbegovic Suad, Uzunovic Nermina Zaimovic, "Determination of the Optimum Blank Shape in Rectangular Cup Drawing", "Trends in the Development of Machinery and Associated Technology", pp 881-884, 2009.
71. Thiruvarudchelvan S., Wang H.B., Seet G., "Hydraulic Pressure Enhancement of the Deep-Drawing Process to Yield Deeper Cups", Journal of Materials Processing Technology, Vol. No. 82, pp. 156–164, 1998.
72. Thiruvarudchelvan S., Tan M.J., "Fluid-Pressure-Assisted Deep Drawing", Journal of Materials Processing Technology, Vol. 192-193, pp 8–12, 2007.
73. Tommerup Soren, Endelt Benny "Experimental Verification of a Deep Drawing Tool System for Adaptive Blank Holder Pressure Distribution", Journal of Material Processing Technology, Vol. 212 pp 2529- 2540, 2012.
74. Thuillier S., Manach P.Y., Menezes L.F. "Occurrence of Strain Path Changes in a Two Stage Deep Drawing Process", Journal of Material Processing Technology, Vol.210, pp 226-232, 2010.
75. Van Tung Phan, Jochen Katja, Bohlke Thomas "Simulation of Sheet Metal Forming Incorporating EBSD Data", Journal of Material Processing Technology, vol.212, pp 2659-2668, 2012.

76. Volk Mihael, Nardin Blaz, Dolsak Bojan, "Application of Numerical Simulations in the Deep-Drawing Process and the Holding System with Segments' Inserts", Journal of Mechanical Engineering, vol. 57, Issue No. 9, pp 697-703, 2011.
77. Wan Min, Yung Yu-Ying, Li Shuo-Ben, "Determination of the Limiting Drawing Coefficient in the Deep Drawing of Conical Cups", Journal of Materials Processing Technology, vol.114, pp114-117, 2001.
78. Wifi A, Mosallam A, "Some Aspects of Blank-Holder Force Schemes in Deep Drawing Process", Journal of Achievements in Materials and Manufacturing Engineering, Vol. 24, Issue No. 1, pp 315 – 323, 2007.
79. Wu J., Balendra R., Qin Y., "A Study on the Forming Limits of the Hydro-Mechanical Deep Drawing of Components with Stepped Geometries", Journal of Materials Processing Technology, vol.145, pp 242-246, 2004.
80. Xu Dongkai, Chen Jun, Tang Yucheng, Cao Jian, "Topology Optimization of Die Weight Reduction for High-Strength Sheet Metal Stamping", International Journal of Mechanical Sciences, vol. 59, pp 73-82, 2012.
81. Yang T.S. "Investigation of the Strain Distribution with Lubrication During the Deep Drawing Process", Tribology International, vol. 43, pp 1104–1112, 2010.
82. Zhao S.D., Zhang Z.Y., Zhang Y., Yuan J.H. , "The Study on Forming Principle in the Process of Hydro-Mechanical Reverse Deep Drawing with Axial Pushing Force for Cylindrical Cups", Journal of Materials Processing Technology, vol. 187-188, pp 300-303 2007.

AUTHORS

First Author – Chandra Pal Singh, PhD Scholar, MANIT Bhopal chandraid@gmail.com
Second Author – Dr. Geeta Agnihotri, Profeesore MANIT Bhopal.
Correspondence Author – Chandra Pal Singh, PhD Scholar, MANIT Bhopal chandraid@gmail.com, 09826227054.