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Analysis of Deep Drawing Process- A Review

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Abstract : Deep drawing is a class of sheet metal forming process used for manufacturing of cups, beverage cans etc. In recent years, it has got a very high industrial importance. Design of material, geometrical and processing parameters for deep drawing is a crucial step. Most of the time these parameters are designed based on shop floor experiences and trial and error approach. But in recent years computer simulation based designs have become very popular. Huge amount researches, on various aspects of deep drawing, have been carried out worldwide. While doing a literature survey on the topic, we found only one survey article (Jaroslav Mackerle, 2004). Unfortunately that too is not reviewed. This study is an attempt to present a collection of more that 270 latest articles with critical review. It is hoped, this review work will help cut short the time of literature survey of researchers working in this field.

Keywords: Deep drawing, blank holder, earring, wrinkling, springback

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1. INTRODUCTION

Deep drawing is the metal working process used for the shaping flat sheets into cup-shaped articles (Fig.1). When the drawn cup is deeper than one half of its diameter, this kind of drawing is called as deep drawing otherwise it will be a shallow drawing. Common shapes produced by deep drawing are cylinders for aluminum cans, cups for baking pans, enclosure covers for oil filters and fire extinguishers. Industries benefited by deep drawing are aerospace, beverages, automobile, dairy, lighting, pharmaceuticals, and plastics etc. Most of the time, the ductile materials, which can be formed, using this process, include aluminum, copper, and steel. Various alloys of Magnesium and Aluminum are also being used for the deep drawing process. The implementation of the deep drawing process involves a lot of skilled labor as to manufacture deep drawn parts require engineer-designed operations such as deep drawing presses which are relatively expensive. Accessories such as molds, tooling plates and columns are required to manufacture deep drawn parts. While a mould is needed for stretching the material over the mould's edge to produce the required shape, a tooling plate or column is needed as a surface for holding work pieces. Pressing operations and deep drawing operations are generally completed using mechanical presses using flywheels to provide kinetic energy. Hydraulic presses are also used. A schematic of deep drawing is shown in Fig.2. Stresses developed in the sheet during the drawing play very important role in the quality of the product such as thinning and wrinkle. Natures of stresses are different in flange and walls (Fig.3). In flange, hoop stresses are compressive and radial stresses are tensile, causing wrinkle. Stresses in the wall are tensile both ways causing thinning and fracture. To avoid wrinkle compressive stress are applied on the flange through blank holder force. There exists an optimum blankholder force (BHF). If BHF is more than this value it will obstruct the material flow in the die resulting in thinning, necking or fracture. At an intermediate stage during the deep drawing operation, the workpiece is subjected to the state of stress as shown in the figure. In flange, the radial tensile stress is due to the blank being pulled into the cavity, and the compressive stress normal to the element is due to the blank holder pressure. The cup wall, which is already formed, is subjected principally to a longitudinal tensile stress, as shown in the figure. The punch transmits the drawing force through the walls of the cup and to the flange that is being drawn into the cavity. The tensile hoop stress is caused by the cup being held tightly on the punch and its contraction under tensile stresses in the cup wall.

The basic and most important parameters of deep drawing are:

a) Mechanical properties of the sheet metal
b) The ratio of blank diameter to punch diameter
c) The clearance between the punch and the die
d) Punch and die corner radii
e) Friction and lubrication at the punch, die, and work piece interfaces and speed of the punch

Seeing the dependencies of large number of parameters, optimum design of geometrical, material and processing parameters is a difficult job. Most often design parameters are arrived at via shop floor experiences and trial and error approach. In recent years, computer simulation has got lot of importance for such application. While doing literature survey on deep drawing, it was felt; there is no dedicated review article available in the literature. The only article, we came across was by Jaroslav Mackerle (2004) and this also is not reviewed. It was felt to carry out a literature survey, especially for the benefit of neophyte researchers, and this article is the outgrowth of that very idea. High quality articles, appeared in the prestigious journals, are given priority. It is felt, this work will reduce the burden of literature review to certain extent.

2. DEEP DRAWING ANALYSIS

Analyses of the deep drawing processes have drawn attention of researchers from the quite sometime. Strides have been made on, experimental, analytical and numerical fronts. In this section articles dealing with generalized analysis of deep drawing are included.

2.1 Experimental and Analytical Methods

Marques and Baptista (1990) compared analytically obtained load-displacement curve with the experimental ones. Yossifon and Tirosh (1991) reported that the final geometry of the product depends on the overall history by which the fluid pressure-path is operated during the drawing process. Yang, Li and Xu (1992) analyzed residual tangential stresses and the content of induced martensite transformation in two kinds of stainless steel using X-ray diffraction. Pasierb and Wojnar (1992) investigated deep drawing and drawing processes of thin walled products using ultrasonic vibrations. Thiruvarudchelvan and Travis (1992) designed, fabricated and tested a novel hydraulic short-stroke device for deep drawing. Yamaguchi, Kanayama, Parsa and Takakura (1993) developed a new deep drawing process to facilitate small-lot production of deep cups with large drawing ratio. Yang and Lee (1993) proposed a systematic energy approach to analyze the three-dimensional sheet metal forming of noncircular cups with complicated shape. Courbon and Duval (1993) investigated evolution of material hardening resulting from the canmaking operations of aluminum beverage. Shirizly, Yossifon and Tirosh (1994) utilized hydromechanical process to study the roles played by die curvature, interfacial friction, material hardening etc. on deep drawing performance. Les and Volk (1994) showed that hydrostatic deep drawing had an edge over classical methods. Ceretti, Giardini and Maccarini (1995) studied effects of technological parameters, such as strain rate, type of lubricant, die-punch clearance and sheet-metal thickness, on drawing force and deformation of deep drawing of non-symmetrical bodies. Leu (1997) investigated effects of coefficient of friction, radius of die and thickness of blank for evaluating the maximum drawing load at a particular drawing ratio in the cup-drawing of a cylindrical cup with a flat-nosed punch. Jimma, Kasuga, Iwaki, Miyazawa, Mori, Ito and Hatano (1998) developed an experimental setup with the blank-holder or die plate vibrated in a radial mode. Thiruvarudchelvan and Wang (1998) developed a hydraulic-pressure augmented deep drawing process to draw cups at large draw ratios. Zhang and Danckert (1998) worked on the development of hydro-mechanical deep drawing of sheet components with concave features. Wan, Yang and Li (2001) obtained limit load during conical cup drawing using Swift's instability criterion and proved it experimentally to be accurate. Schuocker (2001), based on mathematical analysis of laser-assisted deep drawing, showed that even much larger reductions were feasible. Haupt and Barschdorff (2001) proposed an approach for pattern recognition in the frequency domain using characteristics of mechanical waves and laboratory tests with dynamic load. Fu and Huang (2001) developed a new deep-drawing technology of sheet-metal forming by way of flexible-die forming using a viscoplastic pressure-carrying medium. Neutz, Ebeling, Hill, Konig, Klose and Muller (2002) carried out deep drawing experiments using gas generator materials. Thuillier, Manach, Alves and Menezes (2002) developed a device to perform deep drawing tests on a classical tensile machine which was also simulated using dynamic explicit finite element code Pam-Stamp. Park, Huh and Kang (2002) investigated the effects of blank shapes using three kinds of blank shapes and three frictional conditions. Colgan and Monaghan (2003) determined the most important factors influencing deep drawing process using design of experiments and statistical analysis. Fereshteh and Montazeran (2003) worked on comparative estimation of the forming load in the deep drawing process using analytical, numerical and experimental techniques. Gotoh, Yamashita and Itoh (2003) worked on an experimental study on the deep-drawing of metal-wire cloth. Lang, Danckert and Nielsen (2004) proposed hydromechanical deep drawing (HDD) with uniform pressure onto the blank and investigated in detail both primarily in experiments and simulation. Zhang, Zhang, Wang, Yu, Xu and Wang (2004) carried out thermal deep drawing experiments used in forming of Mg alloy. Behrens, Doege and Springub (2005) gave analytical model for deep drawing processes of rotationally symmetric cups. Park and Yarlagadda (2005) developed a surface area calculating system for design of blank shape for non-axisymmetric deep drawing products with elliptical shape. Lang, Danckert, Nielsen and Zhou (2005) investigated the forming of a complex cup locally constrained by a round die based on an innovative hydro mechanical deep drawing (HDD) method.

2.2 Numerical Techniques

Probably finite element method (FEM) is the most popular numerical tool used for deep drawing simulations. Finite element analysis (FEA) and computer aided design (CAD) provide most powerful platform for its virtual simulation. Shinagawa, Mori and Osakada (1991) simulated plastic deformation and temperature distribution in deep drawing of stainless steel sheets with deformation-induced martensitic transformation by using the rigid-plastic FEM. Doege and Eldsoki (1992) used FEM for prediction of cracks in deep drawing and stretching processes. Kampus and Kuzman (1992) analysed deep drawing without blankholder with special emphasis on workpiece geometry. Elmouatassim, Jameux, Thomas, Mehrez and Milcent (1994) carried out three dimensional explicit finite element simulation of multi-operation deep drawing process. FEM was used by Shaghouei, Webb and Kormi (1995) as a flexible aid in the simulation of deep drawing and multiple rigid-body collisions. Yang, Jung, Song, Yoo and Lee (1995) made a comparison of the effectiveness of implicit, explicit and iterative implicit/explicit finite-element analysis methods for the analysis of static and dynamic sheet-forming problems. Huo and Nakamachi (1995) evaluated the dynamic explicit/ elasto-viscoplastic finite-element method in sheet-forming simulation. Estimation of dynamic effects and the evaluation of numerical schemes of so-called mass scaling, damping scaling and material viscosity are investigated by the approaches of the theoretical formulation and numerical verification. Wang and Zhu (1995) reported numerical and experimental studies of deep-drawing process to analyze axisymmetric deep-drawing process. Kaiping, Habraken and Bruneel (1995) simulated a square-cup deep-drawing with different types of 2D and 3D finite elements. Sato, Shimizu, Sano and Fuchizawa (1995) carried out square cup deep drawing of thick plate by multi-axial loading. Finite element analysis was performed in order to verify the validity of the proposed method. Mamalis et al (1996) carried out finite-element simulation of the deep-drawing of square sections of coated steels. The proposed FE model predicts the load curves and the material flow efficiently. Eriksen (1997), using numerical simulation, showed the influence of die geometry on tool wear in deep drawing. Shim and Yang (1997) analyzed cylindrical and square cup drawing using both membrane analysis and shell analysis by the elastic-plastic finite element method. Jung et al (1998) combined step-wise implicit–explicit finite-element simulation of auto body stamping processes. Ferran et al (1998) and Colgan et al (2003) explained the importance of computer-aided design of bending drawing test. Park, Choi, Kim and Choi (1999) developed a CAD/CAM system for axisymmetric deep drawing processes. Menezes and Teodosiu (2000) worked on three-dimensional numerical simulation of the deep-drawing process using solid finite elements accounting the large elastoplastic strains and rotations and Hill's orthotropic yield criteria. Abichou, Zahrouni and Potier-Ferry (2000) presented an asymptotic numerical method to simulate a 3D hemispherical deep-drawing of a circular sheet. Park, Bae and Kang (2000) developed computer aided process planning (CAPP) system for rotationally symmetric deep drawing products. Parsa, Yamaguchi and Takakura, (2001), examined the behavior of two-layer aluminum–stainless-steel (AL-SUS) laminated sheets during deep drawing, direct and reverse redrawing processes (first and second drawing stages), by simulations and laboratory experiments. For the simulation a rigid-plastic finite element program has been used. Shi, Wei and Ruan, (2001), based on a one-step simulation algorithm, developed a finite element program for direct prediction of blank shapes and strain distributions for desired final shapes in sheet metal forming. Manach, Oliveira, Thuillier and Menezes, (2002) compared the numerical simulation of the mechanical behaviour of steels under different loading with experimental results. Gantar and Kuzman, (2002) studied the stability of the production process of deep drawing of a rectangular box by experiments and numerical simulations. Kang and Park (2002) investigated process sequence design and constructed a computer-aided process planning system for non-axisymmetric deep drawing products with elliptical shape. Kirby and Wild (2000) modeled the workpiece as a deformable body using a quadrilateral axisymmetric element. Zhang et al (2000) analyzed deep-drawing process using the explicit finite element method considering various process parameters. Choi, Choi, Na, Bae and Chung (2002) reported an application of intelligent design support system for the deep drawing process of the circular cup. Liu, Peng et al (2004) worked on numerical and FE analyses that can be applied to various aspects of deep-drawing such as the large elastoplastic strains and rotations. Thiruvarudchelvan et al (2000) and Lang et al (2004) investigated the hydraulic-pressure deep drawing process considering various parameters. Natarajan et al (2002) carried out numerical simulation and experimental validation of deep drawing of circular blanks into axisymmetric cylindrical cups at different draw conditions and emphasized on the flange thickness variation. Ahmed and Sekhon (2003) incorporated the concept of adaptive meshing for finite-element analysis of the deep-drawing process. A comparative estimation of the forming load in the deep drawing process was done by Saniee et al (2003). Duchene, Godinas, Cescotto and Habraken (2003) presented a constitutive law based on Taylor's model implemented in a non-linear finite element code. FEM and neural network prediction on hydrodynamic deep drawing was studied by Lin (2003). Geiger, Merklein and Kerausch (2004) presented a finite element based procedure to determine adequate laser parameters for the heat treatment process to enhance the forming limits. Naceur et al (2004) developed “one step” finite element method called the Inverse Approach (IA) to estimate the large elasto-plastic strains in thin sheet metal parts obtained by deep drawing. Incandela, Tabourot, Porret, Balland, Arrieux and Ducher (2004) carried out finite element simulations of deep-drawing operations including spring-back effect until the occurrence of strain localisation. Ku and Kang (2004) illustrated the application of process modeling to deep drawing and redrawing operations. Moura et al (2004) calculated the failure analysis of a deep drawing die in the manufacturing of an automotive shock absorber cap. Qin and Balendra (2004) worked over the detailed considerations that are required for the forming of components with convex features.

Tabourot, Vacher, Coudert, Toussaint, and Arrieux, (2005) presented a purely numerical criterion to determine the onset of necking during finite element simulation of a deep-drawing process. Vacher et al (2005) carried out FE analysis of deep drawing process in order to determine the strain localization. Zhao, Wang et al (2005) presented a feed-forward neural network model based on the LM algorithm (put forward by Levenberg and Marquardt) which established to realize real-time identification of material properties and friction coefficient for axisymmetric workpiece. Endelt, Nielsen, Danckert (2006) presented a new framework for the design of controllers for highly non-linear systems. Peng, Zhong-qin, Long and Muamme (2006) worked on parametric analysis of warm forming of aluminum blanks with FEA and Design of Experiments (DOE). Zhang et al (2006) carried out numerical and experimental studies on deep drawing of magnesium alloy sheets at warm temperatures. Experiments were carried out to verify the computer simulation results. Garc´ia et al (2006) worked on the FE modeling using axisymmetric elements and experimental validation of steel deep drawing processes. Manabe, Shimizu and Koyama (2007) investigated the product accuracy in two-stage cylindrical cup deep drawings**.**

3. BLANK HOLDER FORCE (BHF)

The blank holder plays a key role in regulating the metal flow by exerting a predefined blank holder force (BHF). When selected properly, BHF can eliminate wrinkles and delay fracture in the drawn part. The blank holder pressure is generally 0.7 % to 1.0 % of the sum of the yield and ultimate tensile strength of the sheet metal. It is useful in controlling flow of blank into the die cavity. Draw beads are helpful in reducing blank holder forces, as stiffness is imparted to flange by bent regions at the beads. Yossifon, Tirosh (1992) examined the feasibility of replacing the rigid blankholder with a 'soft' hydrostatic fluid pressure. Thiruvarudchelvan, Travis (1992) designed, fabricated and tested a novel hydraulic short-stroke device for deep drawing. Punch force and the blank-holder force were calculated at several values of the punch stroke. Thiruvarudchelvan, Loh (1994) discussed differences between the theoretical and the experimental BHF variations. Jung et al (1995) worked on an improved method for the application of BHF considering the sheet thickness in the deep-drawing simulation of planar anisotropic sheet. Traversin et al (1995) worked on closed-loop control of the blank-holder force in deep drawing using finite-element modeling. Thiruvarudchelvan (1995) presented the concept of hydraulic short-stroke device that applies automatically a blank-holder force proportional to the punch force. Shulkin, Jansen, Ahmetoglu, Kinzel, Altan (1996) conducted FEM simulations for net shape manufacturing to investigate the influence of elastic deflections of the blank holder. Siegert, Ziegler, Wagner (1997) used a special die with hydraulically supported segmented binders to built up a closed loop control to vary the BHF during the forming process. Lembit et al (1998) proposed the techniques for minimization of undesirable dynamic effects in quasi-static FE simulation of deep drawing. Gunnarsson, Asnafi, Schedin (1998) developed new blank-holder system with degressive gas springs and evaluated it for axi-symmetric deep drawing. Thiruvarudchelvan and Wang (2001) described a method of reducing the blank-holding force applied on the flange of the cup, and steps taken to reduce the speed of the emerging cup to acceptable values. Kampus, Balic (2003) described experiments involving the deep drawing of tailored blanks without a blankholder. Koyama, Manabe et al (2003) proposed virtual processing algorithm with intelligent BHF which did considerable time and cost saving. Peled, Rubin, Tirosh (2004) focused on plastic flow beneath the blank-holder using Cosserat theory of a generalized membrane. Sun, Chen, Lin, Zhao (2004) presented a new optimization algorithm and adaptive response surface method to determinate the optimal BHFs for deep drawing of a aluminum rectangular box. Park, Ku, Kang, Hwang (2004) achieved multistage deep drawing of rectangular configuration with an extreme aspect ratio, focusing on the process design including BHF. Sheng et al (2004) proposed an adaptive FEM simulation for prediction of variable blank holder force in conical cup drawing. Wang and Lee (2005) proved that space-variant blank-holder force could improve the quality of forming to achieve a targeted shape product. Gavas and Izciler (2006) presented innovative blank holder concept of square cup to reduce friction between blank and blank holder. Yagami, Manabe and Yamauchi (2007) proposed an algorithm for controlling blank holder motion by temporarily allowing wrinkling such that blank holder force is extremely low. Gavas and Izciler (2007) studied the effect of blank holder gap of square cups of ETIAL-8 sheets by experimental approach. Savas and Secginet (2007) investigated the effects of blank holder and die shapes using five kinds of blank holder and die shapes.

4. FORMING LIMIT DIAGRAM

Due to the complexity of sheet-forming operations, simple mechanical property measurements made from the tension test are of limited value. Over the years a number of laboratory tests have been developed to evaluate the formability of sheet materials. A useful technique for controlling failure in sheet-metal forming is the FLD. The surface of the sheet is covered by a grid of circles, produced by electrochemical marking. When the sheet is deformed, the circles distort into ellipses. The major and minor axes of an ellipse represent the two principal strain directions in the stamping. The strain in these two directions is measured by the percentage change in the lengths of the major and minor axes. These strains, at any point on the surface, are then compared with the Keeler-Goodwin diagram, also called forming limit diagram, for the material (Fig.4). Strain states above the curve represent failure; those below do not cause failure. The failure curve for the tension-tension region was determined by Keeler and is nearly fixed for a variety of low-carbon steels. Other metals such as aluminum have a different curve. Mechanical properties, which are considered to be important sheet formability, are average plastic strain ratio(r) and strain hardening exponent (n). The higher the normal anisotropy and strain hardening and lower the planer anisotropy the greater will be the sheet formability. Sheets having improved formability are called extra deep drawing (EDD) sheets.

Takuda, Mori, Fujimoto, Hatta (1996) predicted fracture initiation site and the forming limit using ductile fracture criterion and compared with experimental observations. Paul, Ray (1997) evaluated formability and impact properties of three commercially produced hot-rolled deep-drawing quality steels. Takuda et al (1999) worked on the formability of a magnesium-based alloy, AZ31, sheet and examined experimentally using Erichsen tests. Wan, Yang, Li (2001) derived equations of the forming limit curves expressed by limiting drawing coefficient. Kohzu, Yoshida, Somekawa, Yoshikawa, Tanabe, Higashi (2001) investigated fracture mechanism and forming limit of commercially rolled sheet of magnesium alloy AZ31 in cylindrical deep-drawing below 473^0 K. Oh, Kim, Park (2002), investigated the effect of sulfur on formability in galvannealed Ti bearing interstitial free steel sheets fabricated with different sulfur contents. Ueda, Kanai, Amari (2002) reported that paint films, which exhibit high elongation and low elastic strain energy have good formability. Kumar et al (2002) studied the formability analysis of extra-deep drawing steel. Yang, Yu, Li, Sun (2003) developed a new ductile fracture criterion and proved that it is reliable to predict the forming limit in deep drawing.

Wu et al (2004) and Lang et al (2004) proposed various simulation and mathematical models for the FLD. Samuel (2004) worked on numerical and experimental studies of forming limit diagrams in metal sheets. Ambrogio, Filice, Palumbo, Pinto (2005) succeeded in enhancing the formability by localised heating of the blank using an electric heater. Oh, Chan, Oh, Han (2006), to predict the forming limit for hydro-mechanical deep drawing of steel sheets, the ductile fracture criteria were integrated into a finite element simulation. Huang, Tyng-Bin et al (2006) studied the formability of non-isothermal deep drawing of AZ31B sheets using experiments and finite element analysis. The experimental results showed that the highest limit drawing ratio, 2.63, is at forming temperature of 260^0 C for 0.58 mm thick sheet which is in good agreement with the simulation results. Lee, Kim, Kim, Kwon, Choi, Lee (2007) predicted forming limit at elevated temperature using FLD developed based on diffuse necking. Zhao, Zhang, Zhang, Yuan (2007) developed a novel device of hydro-mechanical reverse deep drawing with axial pushing effect for cylindrical cups which enhanced the formability. Hama, Hatakeyama, Asakawa, Amino, Makinouchi, Fujimoto, Takuda (2007) reported that the sheet hydroforming (SHF) process gave much better formability than the conventional press forming process.

5. DEEP DRAWABILITY

Deep drawability or limiting drawing ratio (LDR) is defined as the maximum ratio of blank diameter to punch diameter that can be drawn without failure. Ohsawa, Ikeda (1993) carried out numerical and experimental studies on LDR of pure aluminum and zinc sheets for varying geometries. Parsa, Yamaguchi, Takakura (1993) investigated partially thickened blank to increase the LDR. Iseki, Sowerby (1993) used analytical tool for predicting the LDR of prismatic cups. Eldomiaty, Shabara (1995) theoretically analyzed the idea of applying hydraulic pressure in the radial direction on the periphery of the blank to improve drawability. Takuda, Mori (2002) reported experimental and numerical studies of the formability of an austenitic stainless steel sheet in warm deep drawing. Lee and Chun (2005) investigated the variation of deep drawability of STS304 using FEM simulations considering combined effects of mechanical properties and deep drawing processing parameters such as temperature, blank shape and holding pressure. Singh, Kumar (2004) developed experimental facility to conduct hydromechanical deep drawing and obtained higher drawability and more uniform thickness distribution. Changa et al (2006) carried out experimental and numerical studies of warm deep drawing of AZ31 magnesium alloy sheet. The simulation demonstrated that variable blank holder force technology could improve the LDR from 3.0 to 3.5, and decrease the wall-thinning ratio from 15.21% to 12.35%. Gavas, Izciler (2006), in order to improve the formability and limiting drawing ratio (LDR), developed a new method deep drawing with anti-lock braking system (ABS). Results showed, higher drawing height and LDR of the cup could be achieved by the use of ABS. Fazli, Dariani (2006) showed that increasing the friction between blank and die or blank and blank-holder decreases the LDR value. Namoco, Iizuka, Narita, Takakura, Yamaguchi (2007) utilized embossing and restoration for increasing drawability of aluminum alloy sheets for their deep drawing.

6. TEXTURE & ANISOTROPY

The preferred orientation of grains, or "texture", has received a lot of attention because of the important effect it has on the properties of commercial products. Sheets used for deep drawing purpose are manufactured through rolling process. During rolling grains of the sheet material attains preferred orientation resulting in anisotropic sheet. The anisotropy plays a very important role in formability and earring of the drawn component. Darmannnowak, Engl (1991) reported that the hot strip textures could be of great importance for the resulting annealing textures and the according material properties. Daniel, Sakata, Jonas (1991) analyzed and measured textures of five types of deep drawing steels using the series expansion method, modul-r and electromagnetic acoustic (EMAT) techniques. Daniel, Savoie, Jonas (1993) investigated texture evolution induced by tensile deformation and by deep drawing. Results indicated that the initial texture changed drastically after a few percent of plastic strain and evolved towards a single orientation. Nakamachi et al (1995) developed a texture code for the characterization of the sheet forming process. Savoie, Zhou, Jonas, Mac Ewen, (1996) analyzed the earring behaviors of the three materials in terms of the initial strengths of the Cube {100}[100], Goss {011}[100] and R {113}[574] components. Tourki et al (1996) proposed a new model for orthotropic plasticity in sheet metal forming. Effects of the orthotropic sheet in the deep drawing were studied by Nhat et al (1998). The effect of material and forming characteristics on the simulation of the deep drawing of square cups of coated steels can be looked in Mamalis et al (1997). Park (1998) showed that sharp cube component of initial texture remained after deep drawing but the weak beta-fiber disappeared from the fully recrystallized sheet. Choi, Oh, Chung , Barlat, (1998) examined the stability of orientations and texture formations at the sequential strain paths such as flange deformation and wall deformation. Kestens, Jonas (1999) found strong evidence for the operation of a selective growth mechanism during the late stages of recrystallization of ultra low carbon steel that was cold rolled to a reduction of 95%. Choi, Cho, Oh, Chung, Barlat (2000) experimentally investigated texture evolution in AA1050 sheet metals during deep drawing. Choi, Cho (2000) evaluated the FCC sheet metal texture during deep drawing process. Meinders et al (2000) investigated the behaviour of the laminated composite sheets and the texture effect on the deep drawability. Knockaert, Chastel, Massoni, (2001) compared the texture evolution obtained from an elasto-plastic rate-independent polycrystalline material model with experiments. Lu, Chen, Chang, Cheng, Tang, Zhou (2001) investigated texture characteristics and it’s effect on over-bar and delta r values. Duchene, Godinas, Cescotto, Habraken (2002) simulated a deep-drawing application using interpolation method in order to show up the influence of the texture evolution during forming processes. Jiang, Zhang, Zhao, Liang, Wang, Zuo (2002) showed that the r-values calculated with the Modified Maximum Entropy Method (MMEM) are in good agreement with the experimental results. Cherouata et al (2001), Garc´ia et al (2006) and Liu et al (2003) investigated the sheet texture and effects of anisotropy on the deep-drawability. Liu, Sun, Zhou, Tu, Xing, Guo, Tong (2003) studied texture evolution in different process. An optimum technique to improve the deep-drawability of the deep-drawing sheet was put forward. Zhao, Hu, Zuo (2006) investigated effects of electric field on recrystallization texture.

7. WRINKLING

Wrinkles are the surface defects in the form of small waves and folds. During deep drawing when sheet of larger diameter moves into die of lower diameter, large compressive hoop stress arise in the sheet, which causes wrinkling and buckling. Approximately eighty percent of the part failure in automotive pressing can be attributed to wrinkling of the flange or corner region. Wrinkling in the sheet is controlled by blank holder force (BHF). If blankholder force is low wrinkle will form and if high necking will form. Hence BHF should be optimized in order to avoid wrinkling, necking, thinning and fracture. A typical wrinkling in square cup drawing is shown in Fig.5.

Narayanasamy, Sowerby (1994) studied wrinkling using flat-bottomed and hemispherical-ended punches for deep drawing of circular blanks into cylindrical cups through a conical die. Doege et al (1995) predicted necking and wrinkling using Continuum Damage Mechanics (CDM) and extended Gurson model. Breuer, Neitzel, Ketzer, Reinicke et al (1996) performed shear tests for different types of reinforcing glass and carbon fabric both dry and impregnated with a polyamide (PA12) matrix, to understand the mechanisms of wrinkle formation. Ahmetoglu, Kinzel and Altan (1997) determined wrinkling and fracture limits and devised BHF control methods on the forming of aluminum alloys using- computer simulations and blank holding force control. Zeng, Mahdavian et al (1998) developed theoretical model to predict the critical conditions of wrinkling and the number of wrinkles, both at room temperature and elevated temperature. Lei (1998), based on the wrinkle and fracture model, calculated the wrinkle critical tangent pressure and the critical fracture radial tensile stress. Chu and Xu (2001) analyzed flange wrinkling of a deep drawing cup as an elastoplastic bifurcation problem. A closed-form solution for the critical drawing stress is developed based on an assumed nonlinear plastic stress field and the deformation theory of plasticity. Meindersa et al (2000) simulated the tailored blanks and gave experimental verification both results are quite close. Kawkaa et al (2001) found that the most important parameter affecting wrinkling simulation was the initial finite element mesh. Hematian, Wild (2000) assessed the effect of initial imperfections on the initiation of wrinkling in deep drawing operations. Kim, Yoon, Yang, Barlat (2001) introduced bifurcation theory for the finite element analysis of wrinkling initiation and growth. Hematian, Wild (2001) investigated the effect of initial tooling imperfections on the initiation of wrinkling of thick sheet. Correia, Ferron et al (2002) studied plastic yielding and wrinkling using a criterion proposed for transversely anisotropic materials. Kim, Yoon, Yang (2003) studied the influence of stress ratios, mechanical properties of the sheet material, geometry of work piece, and contact condition on the wrinkles using finite element analysis. Correia, Ferron (2003) developed methods to capture the onset of wrinkling on the wall of the blank. Correia, Ferron (2004) investigated onset of wrinkling in sheet metal forming using an analytical approach and finite element (FE) simulations Fan et al (2006) worked on 3D finite element simulation of deep drawing with damage development. Experiments had been conducted to investigate the effect of blank holding force on wrinkling, and determine the position of crack initiation. Narayanasmy, Loganathan (2007), showed that onset of wrinkling took place when the ratio of the plastic strain increment reached a critical value.

8. EARRING

Planer anisotropy of the sheet results in ears to form in the drawn cups by producing a wave edge. The number of ears produced may be 2, 4 or 6. Height of ears increases with increase in planer anisotropy (Hasford and Caddell, 1983). Earring in a typical deep drawn component is shown in Fig.6. It not only necessitates another process like trimming but also puts extra burden in terms of enhanced material and energy consumptions. Naess (1991) carried out experiments to investigate how the rolling texture and earring develop from two widely different annealing textures. Barlat, Panchanadeeswaran, Richmond (1991) established relationship between yield surface shape and earring tendency of flange. Yoon, Song, Yang, Chung and Barlat (1995) carried out finite element analysis of sheet forming using an anisotropic strain-rate potential and the convicted coordinate system model. Chen, Sowerby (1996), based on particular form of anisotropy, predicted four fold symmetrical earring. Hu, Liu, wang (1999) focused on numerical simulation of flange earring of anisotropic circular sheets. Hu, Jian and Guo (1998) worked on FEM simulation of the forming of textured aluminum sheets using Taylor’s model of crystal plasticity. Inala and Wub (2000) worked on FE simulation of earring in textured aluminum sheets using a polycrystal and a phenomenological model. For the polycrystal model, the material behaviour was described using crystal plasticity theory where each material point in the sheet was considered to be a polycrystalline aggregate of a very large number of FCC grains. Kishor and Kumar, (2002) worked on optimization of initial blank shape to minimize earring in deep drawing using finite element method. Li, Zhang, Peng (2004) developed rate-independent crystalline plasticity constitutive model and introduced into elasto-plastic dynamic explicit FEM. Simulation of earring profiles from texture data, by means of a visco-plastic self-consistent polycrystal plasticity approach, was done by Engler and Kalz (2004). Raabe, Roters, Wang (2005) observed that an increase in orientation scatter of certain texture components entails a drop in ear sharpness while for others the effect is opposite. Vahdat, Vahid, Santhanam, Sridhar, Chun, Young (2006) carried out numerical investigation on the use of draw beads to minimize ear formation in deep drawing. Mahmudi, Alaiha (2006) concluded that "non-earing" quality in material can be obtained by proper combination of processing variables such as; homogenization, cold reduction, and annealing cycles. Walde, Riedel (2007) found that earring pattern depended not only on initial texture, but to a large extent also on the evolution of texture during drawing. Engler, Hirsch (2007) simulated the formation of earring from crystallographic texture by means of a polycrystal-plasticity model. Tikhovskiy, Raabe, Roters (2007) developed texture component crystal plasticity finite element method (TCCP-FEM) for the simulation of the earring behavior.

9. SPRINGBACK

In the deep drawing process, when tools are released after the forming stage, the product springs back due to the action of elastic recovery. Because the geometric tolerances can be tight for sheet metal products, this shape deviation can be unacceptable. In many cases springback compensation is needed: the tools of the deep drawing process are changed so that the product becomes geometrically accurate. Bayraktar, Altintas (1996) worked on springback and sidewall curls in 2D-draw bending operation. Hsu, Shien (1997) obtained numerical solutions of springback effect using a total Lagrangian formulation of a finite-strain thin shell theory. Jourdan, Jean, Alart (1998) developed an implicit numerical method to overcome the convergence problems due to strong non-linearities and to simulate spring-back effect. Morestin, Boivin, Silva (2001) predicted the sheet metal's springback after deep drawing for the control of manufacturing processes. Acquisto and Fratini (2001) used measurement technique, based on the shadow Moire method, in order to evaluate the springback phenomenon in deep drawing operations. Liu, Hu, Wang (2002) presented numerical simulation of the springback characteristics of the strong anisotropic sheet metals after unloading. Effects of the planar anisotropy coefficients and yield function exponent on the springback characteristics were discussed in detail. Lee et al (2002) applied implicit finite element method in the study of springback. Viswanathan, Kinsey, Cao (2003) studied springback of a steel channel forming process using artificial neural network and a stepped binder force trajectory. Song, Yao, Wu, Weng (2003) adopted updated Lagrange formulation and elasto-plastic constitutive equation to solve the problem of springback in sheet forming process. Behrens, Yun, Schäffner, Sundkötter, Kröning, Altpeter, Kopp (2005) discussed the effects of relevant forming parameters on springback. Lingbeek, Hu´etink, Ohnimusb, Petzoldt, Weiher (2005) presented the smooth displacement adjustment (SDA) and the surface controlled overbending (SCO) methods to overcome springback. Thomas, Timothy, Henry, Richard (2005) investigated residual stresses by means of neutron diffraction and found that thermal relief of cold work in the initial AISI-1010 cold rolled blank had no discernable effect both on the residual stresses and the springback. Oliveira, Alves, Chaparro, Menezes (2007) evaluated the influence of work-hardening in springback prediction. From the several work-hardening models tested, the differences in springback prediction are not significantly higher than those previously reported for components with lower equivalent plastic strain levels. Jung and Huh (2007) optimized process parameters in order to reduce the amount of springback and improve shape accuracy of a deep drawn product of the channel shape.

10. FRICTION & LUBRICATION

Lin, Wang, Huang (1992), developed a testing device to investigate the mechanism of friction and lubrication by examining optical micrographs of the worn surface and the variation in the surface roughness on the flange during the deep-drawing process. Lin, Lee and Lee (1992) assessed friction coefficient associated with the surface texture by means of eddy-current measurements. Vreede et al (1995) and Pasquinelli, Pisa (1995) worked on the various algorithms to model the contact, with friction, between a deformable body and rigid surfaces. Simulations of square-cup deep-drawing with various friction and material models were done by Ronda, Mercer, Bothma, Oliver, Colville (1995). They used constitutive models of the blank proposed by Estrin and Robinson (Freed, 1991 & Arya, 1989), and two friction models viz. the non-linear pressure-dependent model and a quasi-steady-state sliding model in the finite-element simulation of a prismatic-cup deep-drawing process. Christiansen, DeChiffre (1997) analyzed progressive wear and other surface alteration processes, which take place on deep drawing dies. Skare, Thilderkvist, Stahl (1998) established proportionality between effective output of the friction surfaces and measured effective output of the AE-sensor and applied this in measurements of acoustic emission in deep drawing machineries. By monitoring the acoustic emission in manufacturing machines, they detected different events like galling, cracks, tool wear etc. He, Wang, Zhen, Bao, Luo, Yang, Zhang, Li (2001) introduced a suitable method for testing friction coefficient in deep drawing process. Luo, He, Yang, Zhang, Zhang, Li (2001) measured friction coefficients in different positions on die surface in deep drawing process through probe sensors. Wang, Zhang, He, Lou, Cheng, Jiang (2001) proposed probe test method that reflect disciplinary of friction and lubrication in deep drawing. Lei, Kang, Qu (2002) put forward method of prediction and determination of both friction coefficient and forming force based on no-wrinkle criterion. Hassan, Takakura, Yamaguchi (2003,2003a) developed a new process on friction aided deep drawing in which a metal blank-holder is divided into eight fan-shaped segments. Wang, Lee (2004) investigated friction between blank and punch, blank and die, blank and blank holder to find which one has more influence on the process. Merklein, Giera, Geiger (2004) used tailored hybrids friction stir weld with the best welding parameters in accordance to the mechanical properties of the weld seams, for deep drawing tests of friction stir welded thin sheet. Boher et al (2005) modelled the die radius friction coefficients with respect to the mechanical characteristics of the deep-drawing process-simulator. This model leads to a correlation between the friction coefficient and the degradation evolutions on the die radius. Hassan, Suenaga, Takakura, Yamaguchi (2005), in order to reduce friction, designed an improved metallic blank holder made of two layers, stationary and moving layer divided into four tapered segments. Manabe, Yamauchi, Yagami (2005) proposed a new algorithm for controlling blank holding force and punch speed in order to improve the friction conditions. Oliveira, Alves, Menezes (2006) used Voce type constitutive law to describe the evolution of the friction coefficient over the entire process as function of the contact pressure.

Bauer, Wendtginsberg (1992) discussed applications of biodegradable lubricants during deep drawing of aluminum roll-bonded sheet to improve the lubricant absorption properties. Mahdavian Sm, Shao Zm (1993) developed analytical model for the iso-viscous hydrodynamic lubrication of deep drawing. Manabe, Yang, Yoshihara (1998) proposed a new in-process identification method of material properties and lubrication condition of anisotropic sheet metals using a combination model of artificial neural network and elasto-plastic theory. Yang (1999) predicted film thickness and the strain distribution of full film lubrication and theoretical results showed excellent agreement with the experiment data. Ashbridge, Gilmour, Leacock (2001) presented a new technique of determining the suitability of potential lubricants. Roescher, Tinnemans (2001) proposed new coatings which can perform both a preservation and lubrication. Function of these products is compatible with commercial paints that are generally used for coating of metal products. Gilmour, Paul, Leacock (2002) used a numerical model to combine empirical measurements of friction coefficients. Kataoka, Murakawa, Aizawa, Ike (2004) prepared various ceramic die materials and applied to deep-drawing for various sheet materials without lubrication.

11. TEMPERATURE

Harasyn, Heestand, Liu (1994) observed that the frequency of cracks caused by tensile stress decreased with increasing drawing temperature above the ductile/brittle transition temperature. Johnson, Opie, Schone, Lanagan, Stevens (1996) devised a new method for the construction of high-temperature superconducting magnetic shielding structures for deep drawing. Chang, Chou (1996) investigated single and double temperature processes, in the range 25-150 ^{0}C for better drawability. Sovakova, Kovac, Boruta (1996) studied hot strip finish rolling in the austenitic and ferrtic temperature regions and showed the decrease of finish rolling temperature resulted in substantial reduction of mean deformation. Naka, Yoshida (1998) performed cylindrical deep drawing tests on a fine-grain aluminum-magnesium alloy (5083-O) sheet at various temperatures and found that drawability was strongly affected by temperature. Chen, Huang and Chang et al (2003) worked on deep drawing of square cups with magnesium alloy AZ31 sheets using experimental approach and the finite element method. The test results showed that AZ31 sheets exhibit poor formability at room temperature, but the formability could be improved significantly at elevated temperatures up to 200°C. Groche, Nitzsche et al (2004) analysed deep drawing with tempered tools to show correlation between adhesion and temperature. Zhang, Zhang, Xu, Wang, Xu, Wang (2007) found that rolled magnesium alloy sheets have good deep drawing formability at a forming temperature range of 105-170 ^{0}C. Boogaard, Hue´tink et al (2006) showed from the simulation studies, increasing the temperature in some and cooling other parts of the sheet could improve the formability of aluminum sheet.

12. PROCESS OPTIMIZATION

Li (1991) proposed a method for predicting deep-drawing performance in terms of n and r-values obtained by means of the uniaxial tensile tests. Doege, Schulte (1992) used the theory of plasticity for design of components with regard to failure of material in manufacturing. Bauer, Krebs (1993) used statistical design of experiments method to record more than one significant parameter on a target value in a specific and systematic way to optimize the process. Guida, Li, Messina, Strona (1994) described the main activities performed for achieving efficiency and dissemination of integrated methodology in order to optimize components, dies and processes. A study on process improvements of multi-stage deep-drawing by the finite-element method was reported by Min et al (1995) while working on multi-stage deep-drawing processes, including normal drawing, reverse drawing, and redrawing, to shape the front shell of a master VAC for an automobile. Iseki, Sowerby (1995) studied two processes one for calculation of optimum blank shapes and other for design of blank. Schfinemann Marco et al (1996) predicted the optimized process conditions in deep drawing and ironing of cans. Moshksar, Zamanian (1997) carried out a series of cup-drawing tests to study process optimization of deep drawing of commercial aluminum blanks. Kuwabara, Si (1997) proposed a method of determining optimum blank shapes for the production of irregularly shaped prismatic shells. Zaky, Nassr, El-Sebaie (1998) determined the optimum shape of a blank for the deep drawing of a cylindrical cup without ears. Ohata et al (1998) proposed an optimum process design system for the complex cup drawing and validated it experimentally. Tai, Lin et al (1998) carried out modeling of deep-drawing process using neural networks. Experimental results showed that deep-drawing performance was enhanced using proposed model. Jensen, Damborg, Nielsen, Danckert (1998) attempted to reduce tool wear using the finite-element method and a general optimization technique to re-design the geometry of the draw-die profile of a deep-drawing. Kim, Park, Kim, Seo et al (1998) presented a method of determining an optimum blank shape for non-circular deep drawing processes. Jurkovic, Jurkovic (2000), using mathematical models, showed dependency of deep drawing force and parameters of drawing process like tool geometry and tribological conditions. Hofmann (2001) showed, by softening of the material in the outer zone of deep drawing blanks, an increase of the limiting drawing ratio from 2.1 to 2.6 is possible for the alloy AA 6181A. Pegada, Chun, Santhanam (2002) used a planar anisotropic yield function and error metric to measure the amount of earring in deep drawing of cylindrical cup. Vohar, Gotlih, Flasker (2002) used non-linear optimization procedure for deep drawing process design. Sarkar, Jha, Deva (2004) investigated number of annealing cycles to find the optimum one to result in extra deep drawing. Gantar, Kuman, Filipic (2005) worked on optimization of the deep drawing processes in order to maximize the stability. Tourki, Sai (2005) gave an accurate description of the material plasticity as compared to the Hill quadratic function using a Budiansky yield surface. Li, Huang, Tsai (2006) developed a methodology for formulating an elasto-plastic finite element model to analyze the deep drawing process of the square cup. Groche, Nitzsche (2006) developed new technology to optimize the aluminum sheet forming process concerning forming limits and adhesive wear. Li, Cui, Ruan, Zhang (2006) developed CAE-based six sigma robust design procedure to eliminate effect of uncertainties in design so as to improve the quality. Anand, Shukla, Ghorpade, Tiwari, Shankar, (2007) formulated a multiple response optimization model using fuzzy-rule-based system to optimize manufacturing processes. Sattari, Sedaghati, Ganesan (2007) performed shape optimization of blank contours using numerical procedure based on the coupling of the Total and Updated Lagrangian approach (TUL) and the sequential quadratic programming method (SQP). Zheng, Sorgentle, Palumbo, Tricarico (2007) worked on optimized design of blanks for deep drawing of Mg alloys under non-isothermal conditions.

13. CONCLUSIONS

Deep drawing is an important manufacturing process. Unfortunately there are not many dedicated review article on the topic. While searching a review title on deep drawing, just one citation article was found which covers whole spectrum of sheet forming. To fill this gap, present work was taken up. In this review paper large number of articles covering wide spectrum of deep drawing are refereed. It is hoped this paper will be of great value to the researchers and design engineers working on deep drawing. It will save huge amount of time going into literature survey.

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