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Towards an optimized process planning of multistage deep drawing: an overview

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ABSTRACT

Purpose: To present a concise literature review on the optimization techniques used for the single stage and multistage deep drawing process, and to identify directions for future research. A perspective on a comprehensive optimized computer aided process planning is provided for multistage deep drawing processes. This is an integrated rule base/dynamic programming/finite element approach that minimizes the total number of stages and heat treatment needed.

Design/methodology/approach: Relevant research is classified according to the major process parameters and the optimization techniques used. Main features and major outcome of the applications are presented.

Findings: There is a lack in the literature in providing a comprehensive approach for optimizing the multistage deep drawing process.

Research limitations/implications: Directions for future research towards integrative models for optimizing the multistage deep drawing process that take into consideration economic as well as operational objectives are identified.

Originality/value: This paper provides a guide for researchers in the field of deep drawing and identifies some directions for future research that can be pursued. It also gives some insights to practitioners in that field on how integrated models can improve the economics and the quality of the process planning decisions for multistage deep drawing.

Keywords: Multistage deep drawing; Process planning; Optimization techniques; Integrated approach; Finite element analysis

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1. Introduction

Improving the productivity and cost is a major target of any rational multistage deep drawing process design and planning. This involves appropriate selection of process parameters such as blank shape, blank holding force and punch/die design. Traditionally, such parameters are determined based on experts' judgment [1]. However, in the last decade, there has been a growing interest in the research community to apply modern optimization techniques as a systematic method for determining the process parameters to achieve a specific objective.

The objective of this paper is twofold. First, it provides a concise literature review of optimization techniques for the single and multistage deep drawing processes. Second, it introduces a framework for a comprehensive and practical optimization approaches for the multistage deep drawing. This is an integrated rule base/dynamic programming/finite element approach that minimizes the total number of stages and heat treatment needed.

2. Process parameters

Based on the process parameters commonly considered in the optimization of the single stage and multistage deep drawing processes, two main lines of research are shown to be of utmost interest. The first line addresses the optimization of the deep drawing tooling including the die, the punch, and the blank holder force or pressure to avoid wrinkling and fracture. The second line is concerned with the optimization of the blank shape.

2.1. Tooling and blank holding optimization

The interest in optimizing the tooling and blank holding parameters started three decades ago and continues to be emphasized in many concurrent research works. Some of the noteworthy efforts in this area are discussed hereunder.

Conry *et al*. [2] studied the optimization of the die profile to avoid fracture. They formulated the problem using a mathematical nonlinear programming model. Ragab and Sommer [3] studied the optimization of the blank-holding mechanism and its design parameters which include the forming of the holding down plate, the contact conditions on the flange of the drawn component, and the forces acting on it. Alexeevich [4] proposed the use of an elastic element underneath the blank holder to optimize the pressure applied to hold sheet metal blanks during deep drawing. Eriksen [5] studied the relationship between die edge geometry and the maximum wear and the wear distribution over the die edge. He developed a numerical model to represent this relationship, and verified the model using physical experimentation. The findings of Eriksen [5] were affirmed by Moshksar and Zamanian [6]. They conducted a series of cup-drawing tests for commercial aluminium blanks. Over the ranges of conditions investigated, the drawing process was found to be strongly sensitive to the die and punch-nose radii. Choi and Kim [7] studied the effect of the die shape and the blank thickness as design variables to minimize the difference between the shape of the desired product geometry and the final analysis result after elastic springback.

Several recent papers utilized finite element modelling and simulation to guide the selection of the tool design parameters. Zimniak [8] studied the deep-drawing process of the multi-operational forming of a compressor cover. He demonstrated the benefit of using finite element simulation to select a suitable tool design from different designs to determine the optimum thickness changes in the final product. Kim *et al*. [9] used finite element simulation to identify an unfavourable contact condition between the blank and the die in rectangular cup drawing with large aspect ratio. They proposed a design modification for the tool shape to improve the quality of the final product. A similar investigation was conducted by Ku *et al*. [10] for the multistage deep drawing of a rectangular cup with extreme aspect ratio.

To this point, it should be emphasized that the blank holder force (BHF) is a crucial parameter that influence the success of the deep drawing process, especially for the first drawing stage. It is used to suppress the formation of wrinkles that can appear in the flange of the drawn part. Wrinkles occur due to the increase in the compressive circumferential stress in the flange which reaches an instability limit causing buckling or wrinkling of the sheet metal. When increasing the BHF, it suppresses the formation of wrinkles. However, the large value of the BHF will restrain the blank material from flowing into the die cavity, causing excessive stretching in the wall of the drawn part and fracture would occur. The process limit of tearing, or fracture, results from excessive localized thinning or necking due to tensile instability [11].

Accordingly, the BHF must be set to a value that avoids both process limits of wrinkling and tearing. The range of suitable BHF values is called the process window as schematically shown in Fig. 1. To explain the concept of the process window, consider two cases [12]. In case I (bold lines); the cup drawing process has a wide working window. Thus, there is a wide range for the BHF that gives a complete cup without tearing or wrinkling. However, in case II (dashed lines); the two processes' limits overlap. This results in limiting the maximum possible punch stroke above which wrinkling and/or tearing would occur, which is shown by the dotted horizontal line.

For a certain cup, the range of values for a suitable BHF is affected mainly by the sheet metal properties and process design parameters. For example, for a small die profile radius and large friction coefficient, the range gets smaller. Another parameter that affects the process window is the drawing ratio. For higher drawing ratio a higher BHF will be required to suppress wrinkling due to the increase in the compressive stress in the flange. This will cause the wrinkling limit to move closer to the tearing limit and the possible suitable range for the BHF gets smaller.

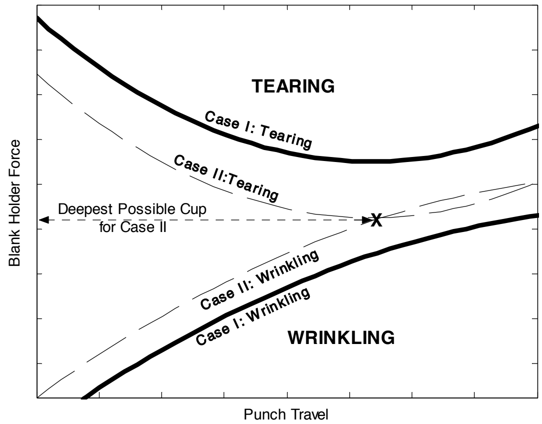

Fig. 1. BHF Working Window (After Gharib *et al*. [12])

Significant work has been carried out by researchers to characterize the onset and/or severity of tearing or wrinkling failure modes. A comprehensive literature review on the different BHF schemes aiming to improve sheet metal formability was provided by Obermeyer and Majlessi [13]. In their review, they listed many linear and non-linear schemes that deal with the control and/or optimization of variable BHF profiles.

In the subject of BHF optimization, Cao and Boyce [14] simulated a conical cup forming process to optimize both a constant and a variable BHF history. They developed a wrinkling criterion based on a combination of energy conservation and finite element analysis, and a tearing criterion based on local strain histories. Their analyses were well-correlated with experimental data, and they were able to design a variable BHF history that resulted in a 16% increase in the forming height of a conical cup. Cao and Wang [15] calculated the critical buckling stress and wavelength as functions of normal pressure using both energy conservation and plastic bending theory. Deng *et al.* [16] developed theoretical models for predicting the drawing fracture load and limit drawing ratio (LDR) for axisymmetric cup drawing using Swift diffuse instability criterion and Hill's theory of plasticity. Kim *et al*. [17] implemented a bifurcation algorithm in their finite element analysis. Their analysis showed the effects of both blank holding force and material anisotropy on the material response.

Adaptive approach was adopted in many works. Sheng *et al*. [18] developed an adaptive simulation strategy that adjusted the magnitude of the BHF continuously during a simulation run. State variables in their model included maximum part thinning and flange wrinkle, as well as sidewall wrinkle amplitudes. A proportional plus integral (PI) controller algorithm was used to adjust the BHF at each time control step. A study similar to Sheng's was carried out earlier by Di Lorenzo *et al*. [19]. In this study a closed loop control system based on fuzzy reasoning was used, and was interfaced with an FEM code in order to determine the optimal blank holder force path. Ben Ayed *et al*. [20] used an adaptive response-surface method to determine an optimal BHF path that minimizes the work done by the punch during the process. Another adaptive control methodology was developed by Strano and Carrino [21] who examined both adaptive control and numerical optimization methods in their analyses, and were able to predict constant and variable blank holder forces while avoiding the limits of tearing and wrinkling, and minimizing spring back. They applied their technique to two parts and determined BHF profiles for the separate cases of minimizing thinning and minimizing spring back. The variable BHF profiles predicted by adaptive control and optimization differed, possibly due to the optimization method finding a local, not global, minimum.

Wifi *et al*. [22] investigated the effect of the coefficient of friction on the optimized blank holder pressure. It is shown that a smoother contact between the blank holder and sheet metal would require higher blank holder pressure to control the flow of the material into a die cavity. Using an optimized blank holder pressure and its corresponding value of coefficient of friction, results in a minimized maximum drawing force. They investigated the effect of the die profile radius on blank holder pressure with different values of drawing ratio at values within the practical range. It was concluded that there is a proportional relation between die profile radius and blank holder pressure. When the die radius increases, the contact area of the blank with blank holder decreases, this may requires high pressure to avoid wrinkling formation.

In their work towards an optimized blank holder force scheme, Wifi and Mosallam [23] conducted a comparative finite element study for a selected set of non-conventional blank-holding techniques including friction actuated, pulsating, and pliable blank-holding. Their results indicated the complexity and interactive nature of the parameters affecting the performance of various blank-holding techniques or force schemes. It has been demonstrated that certain combinations of such parameters would lead to the most favourable working conditions resulting in a successful cup drawing. Furthermore, they emphasized that using the finite element method as an evaluation engine of the objective function used in optimization is very powerful, yet very time consuming. They asserted that combining ideas and concepts of different non-conventional techniques seems to be promising and is worth considering for finite element-based assessment. They concluded that efforts should be made to develop effective optimization techniques to control these parameters and optimize the BHF schemes. One of such effort attempts is made in collaboration with Gharib *et al* [24][25] who used the finite difference method as a solution engine to describe the cup flow. This approach is summarized hereunder.

The BHF can be varied with punch travel either linearly or non-linearly. Gharib *et al*. (2006) [12] developed an optimization strategy for determining the optimum linearly varied BHF scheme for a certain cup model that minimizes the maximum punch force without causing wrinkling or tearing in the cup material. The decision variables include the initial value (intercept) of the BHF function, the slope of the BHF function (either positive or negative slope), and the punch travel. The constraints are defined as to avoid wrinkling and tearing by setting a lower and upper bounds on the value of the punch force respectively. Kawai's wrinkling criterion [26] is adopted. Fracture (necking) is assumed to occur at the point where maximum uniaxial stress occurs in the material. This criterion was discussed by Marciniak and Duncan [27] and applied by Ahmetoglu *et al.* [28]. In order to achieve the optimization objective, genetic algorithms (GAs) are used with the objective of minimizing the punch load.

Gharib *et al*. [12] compared between the thickness strain distribution for the constant BHF and the optimized linear BHF schemes, which is shown in Fig. 2. It is evident that the maximum thinning has decreased by about 22% using the optimized linear BHF scheme. This decrease in thickness strain provides a more uniform thickness at the punch bottom which is a major requirement in the cup forming process.

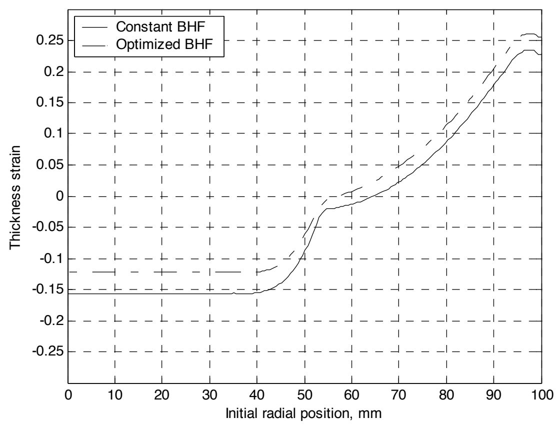

Fig. 2. Thickness strain distributions for the constant BHF and optimized BHF (After Gharib *et al*. [12])

2.2. Blank shape optimization

The selection of an appropriate blank shape and blank mechanical properties helps in reducing scrap and avoiding various types of failure. Iseki and Murota [29] and Iseki and

Sowerby [30] studied the blank shape design for the deep drawing of non-axisymmetric cups using finite element simulation. They considered the elimination of earing as the objective. They developed an inverse finite-element technique to perform the analysis for calculating the blank shapes. Park *et al*. [31] proposed a new blank design method combining the ideal forming theory [32] with a deformation path iteration method based on finite element analysis. Pegada *et al*. [33] studied the optimization of the blank shape with the objective of minimizing earing.

Gea and Ramamurthy [34] presented a numerical optimization model for square shells in which the objective is to maximize drawability, subject to the constraints that fracture failure and draw-in failure do not occur. They concluded that, by considering both the drawability and the non-uniformity of the final flange profile, the circular profile can be considered to be the optimal blank shape for square cup drawing.

Shim and Son [35] and Shim [36] developed an optimization methodology, referred to as the sensitivity method, to determine the optimal blank shape. The sensitivity method is based on an iterative modification of an un-deformed blank shape by moving the nodal positions at the boundary of the blank until the final shape satisfies a target shape.

Naceur *et al*. [37] developed a numerical approach to optimize the shape of the initial blank based on the coupling between the inverse approach used for the forming simulation and an evolutionary algorithm. Kim *et al*. [38] used an inverse finite element approach to determine the optimum blank shape and the intermediate die shapes for multistage deep drawing of elliptical and rectangular cups with large aspect ratio. Park *et al*. [39] carried out finite element analysis to select an optimized blank shape that minimizes the amount of removed material after the trimming process for multistage deep drawing of rectangular cups with extreme aspect ratio.

The main shortcoming of the iterative optimization procedures designed for determining the optimal blank shape design is the large computational time needed. This large computational time results from the large number of iterations of the optimization procedure; while for each iteration, one or more finite element simulation runs are conducted. Hino *et al*. [40] developed a new iterative optimization procedure for determining optimal blank shape based on the interaction of high- and low-fidelity simulation models in order to reduce overall computing time. In the iterative optimization procedure, only the corrected low-fidelity model is used. The high-fidelity model, which requires much longer computing time, is used only for the correction of the low-fidelity analysis and validation of the final solution.

3. Process planning and optimization

Process planning and optimization techniques used in the multistage deep drawing process can be classified into two main categories. The first one, started in the early 1980s, uses rule-bases to determine optimized process parameters that would improve the output of the process. The second one, introduced in the 1990s, is more systematic as advanced statistical techniques are implemented. These techniques present an optimization methodology in the form of online algorithms in which search directions are determined and regularly updated as the outcomes of the process are revealed. In both approaches, a real experiment is conducted and/or a simulation software package that implements the finite element method (FEM) is used to examine the benefit from the optimization approach or the proposed selection of process parameters.

Recently, Wifi and his co-workers [22, 41-46] adopted the strategy of integrating the rule base approach to the dynamic programming optimization methodology. Feasible process plans are simulated using finite element method with full account of formability limits. Process plan leading to maximum thickness uniformity and least deformation severity is considered optimal. For parts with geometrical complexities, more than one deep drawing step is usually required with the possibility of heat treatment. In this case, the objective of the determination of the minimum number of redrawing steps and heat treatments is necessary to reduce production cost. However, it seems that the research work that considered that objective is quite few.

Cao *et al*. [47] developed an optimization approach based on suitable design rules and inverse finite element for constructing suitable die shapes for the first draw and subsequent drawing steps. This approach was capable of reducing the number of drawing steps from 10 to 6 with lower tearing potential; while the press loads are almost identical. Kim and Hong [48] studied the minimization of the number of drawing steps for molybdenum sheet. From parametric study results, the design variables of the multi-stage deep drawing process were selected, and based on the selected parameters, a nonlinear process optimization, based on finite element simulation, was conducted to obtain the optimum multi-stage deep drawing process. They used a simulated annealing optimization approach concurrently with finite element simulation in order to find the safe working process parameters.

Faraji *et al*. [49] used finite element simulation to improve the process parameters for multistage cylindrical shell deep drawing with the objective of maximizing the ratio between the initial blank diameter and the final shell diameter. In a case study, they were able to reach a value of 9 for that ratio. Ramírez *et al*. [50] developed an evolutionary approach for optimizing the multistage forming process of Aluminium cups. Two objectives are considered: the minimization of total process time and the minimization of total process cost. Both objectives are directly related to the minimization of the number of drawing stages. However, they did not take into consideration the option of conducting heat treatment, and their model does not contain constraints that ensure the feasibility of the process plans.

3.1. A rule-based optimization technique

The rule-base technique is a popular approach for developing computer aided process planning (CAPP) systems. The first serious attempt to develop a rule-based (RB) system for axisymmetric deep drawing of monotonic parts is probably that due to Echel *et al*. [51]. This approach was followed in many papers and the works of Sitaraman *et al*. [52], Fang *et al*. [53] and Park *et al*. [54] are worth mentioning.

Wifi *et al*. [41] developed a comprehensive rule-based CAPP system for deep drawing of round and box shapes which was successfully verified via experimental testing and comparison with other experimental works and CAPP systems. A rule-based fast optimization model for optimizing the deep drawing process parameters and minimizing the maximum drawing force, for the first stage of cylindrical shapes, is developed. The process parameters such as stage diameter, die profile radius and blank holder pressure have wide practical ranges. The proposed model attempts to select an optimal value for each parameter that leads to a minimized maximum drawing force that satisfy the no tearing, no wrinkling conditions. The essential technical information and calculations required for design optimization and planning of the drawn parts are integrated into the optimization model. This model, which is solved using a commercial package, called LINGO [55], renders itself for use as a quick approach for decision making in industrial applications.

3.2. Finite element based optimization

Due to the complex nature of the multistage deep drawing process, closed form mathematical models based on theoretical analyses of this process are either difficult to deal with in an optimization approach, or may turn to be unsuitable for realistic applications. Therefore, most of the research work concerned with the optimization of the deep drawing process uses finite element (FE) simulation to guide the decisions conducted by the optimization approach.

Finite element (FE) simulation and analysis provides a fertile environment for improvement and optimization in deep drawing. Furthermore, FE facilitates the implementation of modern and more sophisticated optimization procedures. The literature of adopting the FE in optimizing deep drawing is huge. Because of space limitations, samples of the literature representing the various finite element based optimization techniques used are categorized and summarised hereunder.

Design of experiment, simplex and neural network approaches

Bauer and Krebs [56] are probably the first to introduce the use of the design of experiments (DOE) technique for the optimization in deep drawing. The DOE is a statistical technique that provides a systematic way of selecting the values of the parameters to be used in conducting either real or FE simulation experiments. The DOE provides statistical tools for analysing the experimental results and accordingly determining the parameters that have the large effect on the output of the process. These results can provide a good basis for improving the output of the process by controlling the most effective parameters. Browne and Hillery [57] used the DOE to study the effect of the deep drawing parameters including die geometry, blank-holding pressure, top-ram pressure, lubrication, and drawing speed on the punch load and wall thickness variation.

Ohata *et al*. [58][59] combined both a nonlinear FE analysis code and the nonlinear optimization code to develop a nonlinear solution algorithm, called sweeping simplex method, to search for the global optimum. To overcome the complexity in the mathematical models of the deep drawing process, some researchers worked on developing empirical formulas that are based on the FE simulation results. Such empirical formulas are simple to deal with using a suitable optimization algorithm. Tai and Lin [60] used neural networks to formulate the relationship between the deep drawing process output represented by the dimensional error of diameter and cylinder and the process parameters including material thickness, punch diameter, die-cavity diameter and materials-clearance ratio. Based on the developed neural network model, they applied a simulated annealing optimization algorithm to determine the optimal selection of the above mentioned process parameters.

Inverse approach

A simplified efficient finite element method, called the inverse approach (IA), is developed for sheet metal forming processes. The IA is based on the idea of estimating the large elasto-plastic strains in thin metallic panels. It mainly exploits the knowledge of the 3D shape of the final part, and an iterative scheme is used to find the original position of each material point in the initial flat blank after which it is possible to estimate the strains and stresses in the final part (*vide* section 2.2). Guo *et al*. [61] illustrates the applicability of the IA to deep drawing. Lee and Cao [62] developed an axisymmetric shell element for the multi-step inverse analysis for more accurate prediction of design variables such as the initial blank shape, strain distributions, and intermediate shapes, etc. Naceur *et al*. [37],[63][64] used the IA combined with a mathematical programming algorithm to optimize the restraining forces and then to design the draw beads.

Response surface approach

The response surface methodology (RSM) has been recently used for the optimization in deep drawing. The RSM is an optimization technique that builds on the results obtained by the DOE[65]. It approximates complex design functions, which are usually higher order, using simple first or a second order regression model. Through this approximation, search directions that improve the modelled objective function can be determined. Huh and Kim [1] used the RSM as an optimization technique to satisfy the objective of obtaining a desired state of strain on the forming limit diagram (FLD). The chosen parameters are the blank holder force and the draw-bead force. Jansson *et al*. [66] used RSM and space mapping technique to optimize the draw-in of an automotive sheet metal part. The optimization adjusts the draw bead restraining force in the model such that the draw-in in the FE-model corresponds to the draw-in in the physical process. The conclusion of their study is that space mapping is a very effective and accurate method to use when calibrating the draw-in of a sheet metal process.

Zhang *et al*. [67] pointed out that variability in the deep drawing process may lead to unexpected results which the deterministic models cannot predict. They used a general approach to quantify the uncertainties and to incorporate them into RSM model so as to conduct probabilistic based optimization. They applied the probabilistic design model to find the optimal combination of blank holder force and friction coefficient under the presence of variation of material properties. The result shows that by the probabilistic design, the quality index (average defect rates of wrinkling and fracture) improved (reduced) 42% over the traditional deterministic design. The uncertainty and unreliability of the deterministic optimization models used in deep drawing motivated further researchers to apply quality improvement programs such as six sigma [68].

Genetic Algorithm Approach

Genetic Algorithms (GAs) are known to be able to search through all of the function space, thus it can detect the global minimum of the function. GAs operates by using initial random points (chromosomes) spread throughout the whole search space. This approach was successfully used in combination with the finite difference (FD) method [12,25] as well as finite element (FE) method [69] to optimize linearly varied BHF schemes. In this approach, each chromosome is composed of two load values, which define a linear blank holder force profile. At the beginning of the punch displacement the blank holder force is given by a specified value, and at the end of the punch displacement the blank holder force is given another value - if the two values are equal then the BHF scheme is a constant one. Since the time-span of the punch displacement is defined by the total step time, these two blank holder force values alone determine the BHF profile. Then, at each iteration (generation), these random points (chromosomes) are refined using different operators to spread over more search space to look for the optimum function value. The search ends when a specified number of iterations are completed [70]. Genetic algorithms act by operating on a population of possible solutions, and they function based on the evolutionary concept of “survival of the fittest.” The members of the population are each assigned a “fitness” value based on the degree to which they satisfy the objective under consideration, and members with higher fitness have a better chance of surviving to the next generation. These fitness values are found by applying a metric to each member of the population which is usually given by the objective function value itself. Thus, for the case of a minimization problem, population members that produce lower objective function values are deemed more fit, and are therefore more likely to be selected for reproduction to the next generation.

In his master thesis (under the supervision of Younan, Nassef and Wifi), Levitysky [69] developed a GA optimization strategy for finding the optimum BHF-punch travel scheme which minimizes punch work and avoids the working limits of tearing, wrinkling, and spring-back effect. Minimization of external work is desirable because its value is positively reflected in the manufacturing cost. As done by Gahrib *et al*. [12],[25], he considered linearly varying BHF profiles for optimization and the objective function values (total external work) are evaluated using finite element analysis. He used an ABAQUS finite element model for cylindrical cups which is integrated with a GA code written in the Python programming language available in ABAQUS through its Python scripting interface. This simplifies the procedure of BHF optimization, which now requires only a deep draw analysis input file to the ABAQUS CAE module. The optimization script is called from this module to generate a population of chromosomes, and subsequently begins calling ABAQUS and obtaining objective function values. This optimization procedure being integral to the FEM software eliminates the need of interfacing and exporting data to an external program and it has the versatility in obtaining optimum variable BHF profiles for various geometries of the deep drawn part. The results of Letivesky [69] were generally in support of the finding of Gharib *et al*. [12],[25] as exemplified in Fig.2.

3.3. An integrated rule-based/ finite element and dynamic programming optimization approach

As mentioned earlier, Wifi *et al*. [22] developed a rule-based computer-aided process planning (CAPP) system for multistage deep drawing of round and box shaped parts. The output of this system is used by Wifi *et al*. [44] in a careful finite element simulation to verify the results and adjust the process parameters if needed to assure the success of the multistage deep drawing process. The advantage of linking CAPP with finite element modelling and simulation is that it provides the investigator with a feasible initial state to start the analysis with. The developed approach considers the use of forming limit diagram (FLD) as a basic reference to indicate the possible failure of the part during multistage drawing.

In an attempt to rationalize and optimize the process planning of multistage deep drawing for round or box shapes, recently Abdelmaguid *et al*. [45],[46] developed an integrated RB / dynamic programming (DP) approach to develop alternative feasible process plans which minimize the total number of drawing stages and heat treatments. The plans with least strain severity are investigated by a comprehensive finite element analysis with full account of formability and severity capabilities. The optimum plan is the one giving successful part with least severity, maximum thickness uniformity and least risk of failure. To demonstrate this approach we consider only the box shaped part. For examples for round part consult Abdelmaguid *et al*. [46].

As detailed in [46], the parameter that largely affects the severity of the deep drawing of box-shaped parts is the part corner radius, r_c [71]. The value of the corner radius at a given stage i, denoted $r_{c,i}$, is governed by the drawing rate as represented by the following relationship.

$$m_i \le r_{c,i} / r_{c,i-1}, \qquad i = 1,2,3, .., n \tag{1}$$

The dimensions of the punch at different stages i.e. length ($l_{p,i}$), width ($w_{p,i}$) and corner radius are calculated for box-shape as follows.

$$A'_{p,i} = l_{p,i} w_{p,i}, \quad \text{and,} \quad \frac{l_{p,i}}{w_{p,i}} = \frac{l_p}{w_p} \tag{2}$$

The above relationship assumes that the aspect ratio of the box-shaped part during the drawing operation is the same as the aspect ratio of the required final product. The exact punch area is calculated as $A_{p,i}=l_{p,i}\, w_{p,i} - (4-\pi)\, r_{c,i}^2$.

The height ($h_{p,i}$) at stage i for a box-shaped part is affected by the part geometry as well as the drawing rate as determined by the stage corner radius $r_{c,i}$. For flanged box-shape the part height at stage i is calculated as follows [43].

$$h_{p,i} = \left(\frac{A_f + 2\pi r_c r_t - a.b - (a+b)(2r_c - 2.43 r_b - 2.43 r_t) - 4(f_s + r_c)^2}{2(\pi r_c + a + b)} \right)_i \tag{3}$$

The above equation is very useful in calculating the height for each stage, which provides a guide for selecting the punch stroke length. Here, A_f is the product surface area. The values of a_i and b_i are respectively defined as $l_{p,i}$ - $2r_{c,i}$ and $w_{p,i}$ - $2r_{c,i}$. In the above equation, r_t is the wall flange radius (die profile radius), r_b is the wall bottom radius (punch nose radius) and f_s is the length of the straight part of the flange. For flangeless parts, $r_t = f_s = 0$.

The second constraint that affects the selection of part dimensions is related to strain severity, which increases with the deformation that takes place at the corner, stretch in the radial direction and compression in the peripheral direction. This strain severity is a crucial factor in determining the success or failure of the drawing operation. Based on the traditional assumption that the material at the four corners of the box shaped part could behave similar to cylindrical parts , the severity factor for stage i (E_i), the total strain severity factor (E) and maximum value of strain (E_{max}) may be calculated as follows [46].

$$E = \prod_{i=1}^{n} E_i \le E_{\max}, \quad E_i = \frac{r_{c,i-1}/r_{c,i} + 1}{2} \tag{4}$$

$$E_{\max} = k\left(1 + \frac{e}{100}\right) \tag{5}$$

Here e is the maximum elongation of the material at fracture, in %; E_i is the strain severity factor of stage i and k is a correction factor ranging from 1.0 to 1.2.

Dynamic programming (DP) is a mathematical technique that is based on the idea of separating a decision making problem into smaller sub-problems. Each sub-problem represents a single stage whose solution is used to infer some properties that can be used to guide the solution of the other subsequent sub-problems (stages). The benefit of using dynamic programming is that it requires less computational effort compared to exhaustive enumeration in which all possible solutions to a given decision making problem are evaluated.

In the multistage deep drawing, sub-problems or stages are defined by dividing the range from $r_{c,i}$ to $r_{c,p}$ at an arbitrary stage i into two sub-ranges from $r_{c,i}$ to $r_{c,i+1}$, and from $r_{c,i+1}$ to $r_{c,p}$. The latter range defines the new stage i+1, which is then divided in a similar fashion. Here, there are two decisions to be made at each stage. The first is related to applying heat treatment at the beginning of the stage, except for the first drawing stage, when i=0, as it is assumed that the blank material is initially heat treated. The second decision is related to the selection of the value of $r_{c,i+1}$. Let $\hat{r}_{c,i+1}$ denote the minimum corner radius that can be achieved such that constraints (1) and (4) are satisfied as related to the heat treatment decision made at the beginning of stage i. Traditional process planning approaches work by setting $r_{c,i+1} = \hat{r}_{c,i+1}$ with the aim of exploiting the full drawability of the material at each stage. This approach results in the minimum number of drawing stages when heat treatment is not an option. However, in the general case, $r_{c,i+1}$ can be selected anywhere between $r_{c,i}$ and $\hat{r}_{c,i+1}$. This allows for having different routes for reaching the final product corner radius. Fig. 3 demonstrates how sub-problems are defined and generated. Since the corner radius is a continuous variable, there is infinite number of states in the search space. However, the range of feasible values from $r_{c,0}$ to $r_{c,p}$ can be discretized by using a small increment δ, so that the sub-problems can be defined over the radii $r_{c,0}$ + δ, $r_{c,0}$ + 2δ, ..., etc. The selection of the sub-range size is crucial for the success of the application of dynamic programming to the studied problem. If it is selected to be too wide, the optimal solution might be missed and the obtained solution will be sub-optimal. If it is selected to be very narrow, unnecessary extra computational time and memory will be needed without really improving the quality of the optimal solution obtained. Furthermore, the larger the sub-range size is, the lower the number of process plans will be, leaving the decision maker with few alternatives to select from. Therefore, the application of the proposed technique requires some preliminary investigations by the decision maker through trying experimental values of sub-range sizes until a sufficient number of optimal process plans are generated.

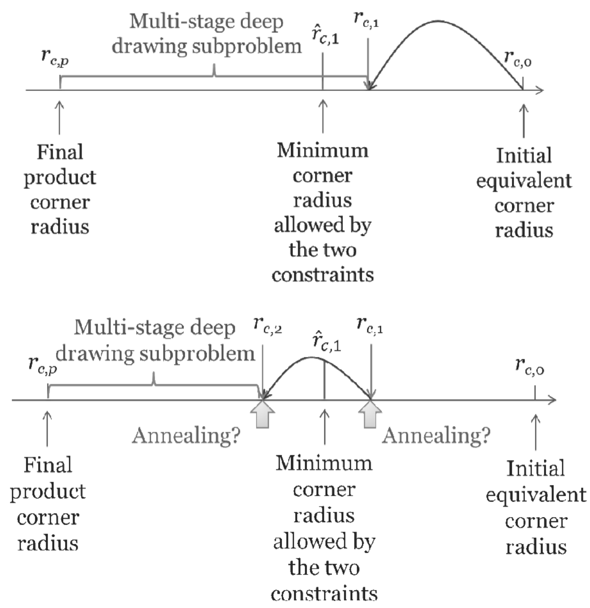

Fig. 3. An illustration of sub-problems generation

Abdelmaguid *et al*. [46] demonstrated the applicability of the developed system by presenting two case studies for box shaped parts. In the first case study, a square part with dimension 58x58x100 mm is considered while in the second example a box with a large aspect ratio of rectangular section with dimensions 342x100x164 mm is considered. Both boxes are made from stainless steel with 1 mm sheet thickness.

The DP approach suggested 11 alternative process plans with a sub-range size of 1 mm for the square part, which could be further tested using the finite element simulation. The optimized plan resulted in a FLD damage factor of 0.48 and final sheet thickness 0.74 mm.

The second case study of the box shape with large aspect ratio used a sub-range size of 0.5, which allowed for generating 10 alternative plans with the same number of three drawing stages and one heat treatment. Two optimized plans (DP plan1 and DP plan2) with the lowest values of strain severity E are tested via finite element simulation to determine their performance as compared to traditional RB plan [22] in producing the required part.

Fig. 4 shows the sheet thickness distribution as resulted from the FE simulation for optimized plans in both the square and rectangular cases. Fig. 5 shows the improvement due to the DP plans in the variation of the sheet thickness along the bottom and wall of the rectangular box.

The results in [46] indicated much improvement in the uniformity of thickness distribution and lower severity and damage risk when the proposed integrated RB/DP strategy is adopted. The versatile plans of the DP approach are found to be more rational than the traditional RB plan. Moreover an optimized process plan could be elected leading to minimum strain severity in the produced part [46].

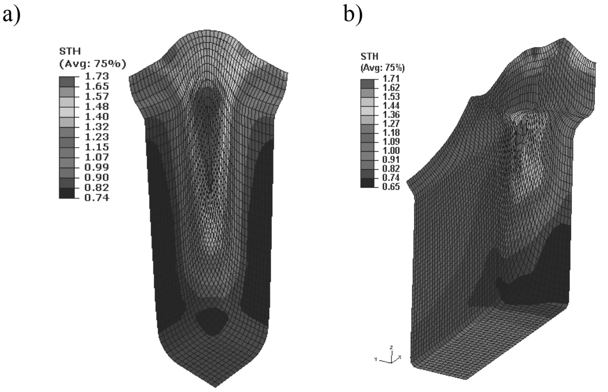

Fig. 4. Thickness distribution for optimized plans for a) Square Box and b) Rectangular Box (Adapted from Abdelmaguid et al., 2012)

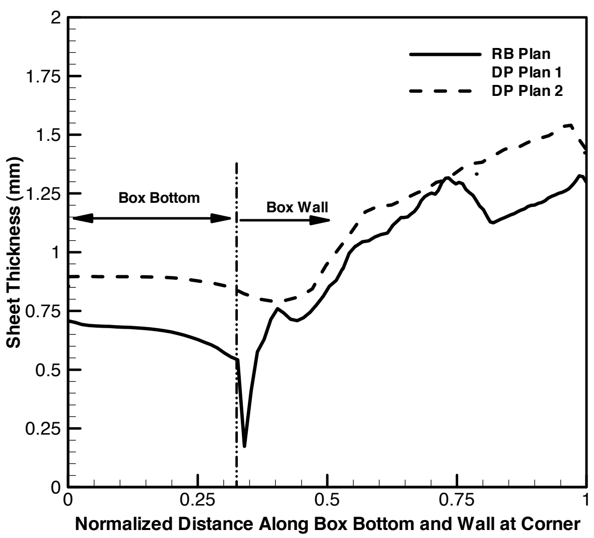

Fig. 5. Thickness distribution along the bottom of and wall of rectangular box. (After Abdelmaguid *et al*. [46])

4. Concluding remarks

The present paper provides a concise literature review of the field of optimization in the single and multistage deep drawing process. A framework for a comprehensive optimization approach for the multistage deep drawing is suggested based on the work done by Wifi and co-workers. An integrated RB / dynamic programming (DP) approach is introduced to develop alternative feasible process plans which minimize the total number of drawing stages and heat treatments. The plans with least severity are validated by a comprehensive finite element analysis with full account of formability and severity capabilities. The optimum plan is the one giving successful part with least severity, maximum thickness uniformity and least risk of failure. Minimization of the number of stages and heat treatments is equivalent to the minimization of external work which is desirable because its value is related to the amount of energy consumed during the deep drawing process, which in turn is reflected in the manufacturing cost. However, it should be noted here that both the traditional RB and integrated RB/DP process plans assume constant thickness during the analysis. This is obviously not true as the sheet thickness varies along the bottom and walls of the drawn part, which is predicted and checked during the finite element validation analysis. The proposed RB/DP + FE validation approach lends itself for use as a rational practical strategy for multistage deep drawing process design.

There is no doubt that the finite element based optimization is powerful and versatile in handling essentially any deep drawn geometry with full account of thickness variation. However, the main shortcoming of the finite element optimization approach stems from the iterative optimization procedures designed to satisfy the objective function. This leads to the large computational time needed since one or more finite element simulation runs are conducted for each generation or iteration. Nevertheless, carrying out the optimization process with finite element evaluations would require many runs in order to fit a proper objective function depending on the number of variables and the degree of fitting. Therefore, the use of finite elements for evaluation will require extensive computational time which varies depending on the part geometry, material properties, loading conditions, and FE model.

Any development leading to the reduction of the time consuming approach is surely welcomed from the perspective of optimization of the deep drawing process design. In that respect, the finite difference (FD) technique lends itself as a fast solution engine for the determination of the cup behaviour with account of thickness variation. No much work using the FD is done and this seems to be an open area of research.

An observation that is worth considering in the light of the present review is the lack of comparative or assessment studies of the various optimization approaches used in the literature. Combining ideas and concepts of different techniques seems to be promising and is worth considering for the optimization of multistage deep drawing process plans.

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