DEVELOPMENTS IN DEEP-DRAWING PROCESS CONTROL REVIEW

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ABSTRACT

This paper presents a review of the developments in deep-drawing process control. Different solutions and their impact are presented. This review is structured considering three important elements of the control: i) deep-drawing control strategies; ii) adjustable deep-drawing process components and iii) process variables. The considered criteria to select the optimal process control take account on these quality considerations: i) formability (no defects like wrinkling due to excessive compression or fracture because of high local tensile stress); ii) dimensional accuracy (e.g. springback caused by elastic recovery); iii) consistency, that represent, minimizing dimensional variations due to the variation of different parameters. The evolution of these elements are presented and discussed.

KEYWORDS: complex deep drawing, process control, FEA, process variables, adjustable components.

1. INTRODUCTION

Sheet metal forming is one of the primary manufacturing processes which have been a modern development. The deep drawn process produces high-strength, lightweight parts more cost-effectively than other methods. Among the advantages offered by deep draw are: rapid press cycle times, fewer operations required to finish a part, the ability to create complex geometries unattainable through other processes.

Deep drawing is one of the most popular metal forming methods available to manufacturers.

When considering the functionality of the end product, deep drawing poses still more advantages. Specifically, the technique is ideal for products that require significant strength and minimal weight.

Deep drawing is a metal forming process in which sheet metal is stretched into the desired part shape. As shown in figure 1 the deep drawing process require a blank, punch, die and a blank holder with or without drawbeads around the edge of the die. The punch pushes downward on the sheet metal, forcing it into the die cavity.

The sheet metal deep drawing technology is one of the most challenging processes in manufacturing.

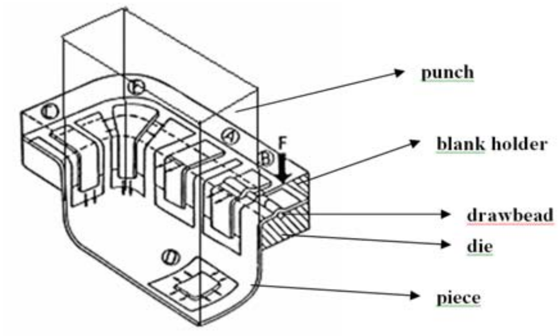

Fig.1: Complex deep drawing process

The size, shape, thickness and deep drawn metal used to produce sheet metal deep drawn part cover a diverse range of variable. Individual variables should be evaluated carefully in order to determine the optimum manufacturing method. The criteria of this optimum take account on three quality considerations [17]: *i)* formability (e.g. wrinkling due to excessive compression and tearing because of high local tensile stress that cause thinning and failure); *ii)* dimensional accuracy (e.g. springback caused by elastic recovery); *iii)* consistency, that represent, minimizing dimensional variations due to the variation of different parameters (e.g. lubrication, material properties, thickness).

The new challenges in this field are: *i)* the use of new materials, and *ii)* a new concept of metal forming like an intelligent next generation technology considering user needs and future technology [9] (Fig. 2).

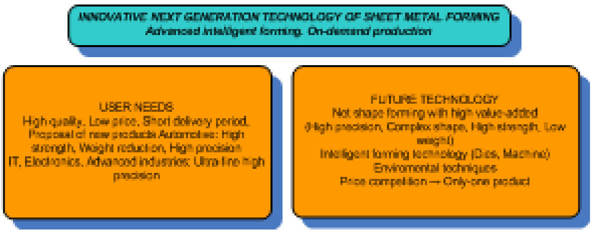

Fig. 2: Roadmap for material process technology in Japan - Materials Process Technology Center [9]

This all considerations determine the motivation for researchers to continue those studies.

This paper presents a review of the developments in deep-drawing process control. Different solutions and their impact are presented. This review is structured considering three important elements of the control: i) deep-drawing control strategies; ii) adjustable deep-drawing process components and iii) process variables. The evolution of these elements are presented and discussed.

2. DEVELOPMENTS IN DEEP DRAWING CONTROL STRATEGIES

Different strategies are developed during the time, respectively:

a). ***Die-Try-Out*** procedure include experimental and numerical analysis in order to determine the optimal process parameters such as geometrical (e.g. die and punch radius, wall angle of the part, geometry of drawbeads) and technological (e.g. clearance between die and punch, blank holder force, drawbeads penetration, punch force trajectory) parameters that control forming process. At the beginning the manufacturers proceeds many experimental cycles. During these cycles' different components of the process – die, punch, blank holder, drawbeads – are physically adjusted or altered by an elaborate method of welding and handing grinding until a proper amount of metal flow in the die cavity is achieved. This method is time and costly consuming and results depend on the manufacturer experience.

FEM software tools play a significant role in reduction of this inconvenient and increase the precision in process design.

During the time many numerical and experimental techniques have been incorporated in die try-out procedure in order to improve time and production costs. Different devices and mathematical models are proposed to identify solutions to reduce springback and to determine the effect of drawbeads in order to optimize utilization [13, 15, 21, 29, 31, and 33].

Between these a recent technology [26] - SCS (Short-Cycle-Stretch forming) - is proposed combining a plane pre-stretching and subsequent deep drawing operation for production of small car body panels with high demands concerning surface quality. This technology is based on a low cost tool design including two opposed bead sets for an alternate bending and unbending of the sheet metal boundary (Fig.3).

During the first step of the process the blank become stretched laterally by the bead sets with three upper and three lower bead elements. The second step is the deep drawing operation starting with the first contact of the punch with the pre-stretched blank. By variation of the shoulder radii of both bead sets and the blank dimension it is possible to realize a predefined strain level during the process.

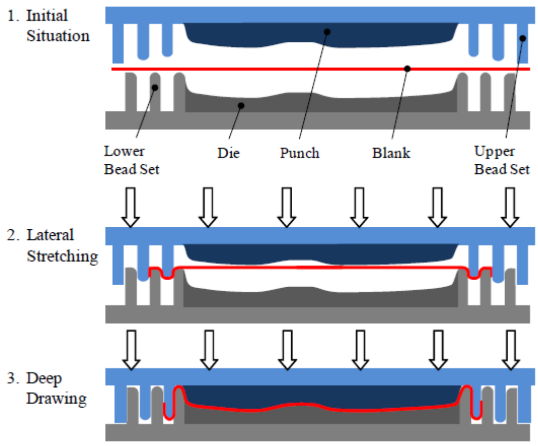

Fig. 3: Schematic view of the drawing process by SCS Tool [27]

The next step of researches, conducted by Papaioanu & all. [27], was the utilization of additional bead elements were located in transversal direction in order to gain higher restraining force in minor strain direction. However, wrinkles and cracks results in the corner region of the drawn part. In order to improve the process and part quality a further development step was conducted so that no wrinkles and crack occur during forming process. In this case, the existing transversal bead set has removed and substituted by a chamfer tool including a conventional draw bead acting five millimeters before process ends and a flexible element for self-adjusting the drawing clearance between die and punch during the process.

All this optimization solutions offer the possibility to obtain good quality for relative simple shapes of car body panels without large uncontrollable deformed surfaces during the process. Additional to this limitation, die try-out procedure offer only open-loop solutions for process control and new control procedures and process design solutions are required.

b). In-Process Control

In-process controls are checks that are carried out before the forming process is completed. The function of in-process control is monitoring and – if necessary – adaptation of the forming process in order to comply with the specifications. In-process control requires a reference trajectory of the manipulated process variables. For identification and adaptation of the reference trajectory during the process different methods are proposed – FEM [6, 39], metamodelling [2, 40], neural networks [36]. All these methods need important computational resources and her development aimed the need of higher speed execution corresponding with the metal forming process speed.

In-process control may be performed in regular intervals during a process step or at the end of a process step. The objectives of in-process control are both quality control and process control. Many researchers chose BHF (blank holder force) and punch force like manipulated process parameters and propose different solutions to identify the reference trajectories and control method. K. Manabe and col. [22, 23] propose on-line simultaneous fuzzy control on both blank holder force and punch speed during the process; Watanabe A. and col. [41] perform a FEM analyses of deep drawing process using a variable blank holder system in order to demonstrate the effectiveness of a servo die cushion on formability; Hayashi and col. [9] propose different applications on servo press – a new type of machine which is controlled by software operations; different slide motion patterns was experimented to demonstrate the effect of: *i)* slide velocity and *ii)* stationary period at the bottom dead (in order to produce an additional of coining pressure) on part quality; Lim and col. [17-19] propose a multi-input multi-output control of blank holder force; a segmented blank holder is proposed and each segment is controlled during the process in order to respect the reference punch force trajectory; L.X. Kong [14] propose an intelligent decision support system for metal forming integrating subjective information (expert knowledge, empirical models, systematic process analysis, etc.) and objective information (structural knowledge obtained from industry, etc.).

The main disadvantage of in-process control is the necessity to systematic design the process controller and reference trajectories.

c). Cycle to Cycle Control

This procedure is based on the statistical process control SPC. Key tools in SPC are control charts, a focus on continuous improvement and designed experiments. The main idea is to develop and continuous update a database of the process variables and extract new information in order to optimize the process and piece quality. Cycle-to cycle control procedure is an off-line process control method and present the disadvantage that it cannot eliminate the influence of disturbances (variation of lubrication, blank thickness and material properties).

3. ADJUSTABLE DEEP DRAWING PROCESS COMPONENTS

In order to achieve the process control, different adjustable elements of the process are proposed. During sheet metal forming process, the BHF (blank holder force) controls the material flow into the die cavity. The optimal flowing of the material plays a critical role in achievement of quality criteria. The process components proposed to be active, by different researchers, are:

- ***blank holder***:

* segmented – Yagami & col. [42] employed a sheet forming simulator with a finely segmented blank holder for stamping process of non-circular parts. The blank holder pressure (BHP) was controlled through an intelligent press control system. The BHP trajectories for each blank holder module were obtained by the virtual database and finite element method. Through the implementation of sequential BHP control according to the trajectory, the potential application of the simulator to non-circular parts was verified and discussed. Wang & col. [39] developed a space variant blank holder force (BHF) system with segmented blank holder to control the strain path during the deep drawing process. They reported that the key advantage is that strain in the forming process can be adjusted in a safe working area without fracture. Lim & col. [17-19] propose a systematic approach to the design and implementation of a suitable multi-input multi-output (MIMO) process controller. This process controller adjusts blank holder force trajectories obtained from the die try-out as process variations occur.

* pulsating – Ziegler & col. [43] shoed that the onset of wrinkling in a blank drawn with a pulsating BHF occurs at a displacement similar to that obtained under a constant BHF equal to the maximum force of the pulsation. The key objective of the researchers was to avoid cracks and wrinkles on the surface by reducing the friction force. This reduction of the friction force was obtained by using the pulsating BHF. Additionally, the pulsating BHF helped to increase the robustness of the process. However, the amplitude and frequency of the pulse would need to be correlated with the lubrication and material properties for a given conditions.

- ***drawbeads***: Micheler [25] and Bohn [1] constructed a multiple-action hydraulic sheet metal device where both drawbead penetration and BHF are controlled (Fig. 4). A PI controller was used to adjust drawbead penetration in order to compensate the deviation between the reference – input - punch force trajectory and the measured - output - actual punch force.

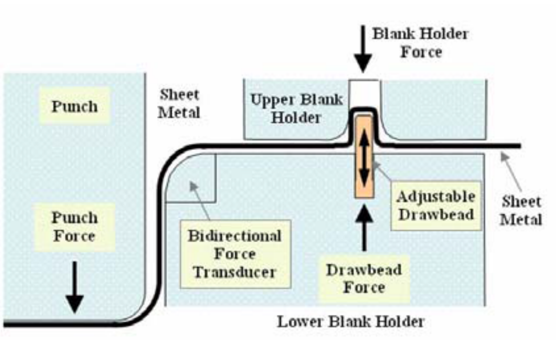

Fig.4: Active drawbead control system [25]

The active drawbead control system can achieve fast response and require smaller energy consumption but this idea is difficult to implement in practice due to complexity and cost in the production of the dies. A reconfigurable forming tool combined with a three-dimensional shape-sensing device and a spatial frequency-based control law is proposed by Walczyk & col. [35] and Hardt [8] in order to minimize part shape errors with respect to a predetermined shape trajectory.

4. PROCESS VARIABLES

Selection of process variable is usually performed considering two criteria: *i)* to be physically measurable and *ii)* to reflect feedback reaction of the material during the process in order to improve deep drawn part quality.

Because the most important relationship for sheet metal forming is stress-strain or force-displacement, the latter two variables are most measured during the process. Different researchers consider a reference trajectory for *punch force* and studies the influence of different other process variables to be manipulated in order to respect this reference trajectory. Failure in the stretch-drawing of sheet metal panels is caused predominantly by either wrinkling or splitting. Wrinkling, which can occur in the flange inside the blank holder or in the unsupported side wall of the deep drawn part, is due to compressive circumferential stresses that result in buckling of the sheet. Splitting, on the other hand, is caused by excessive tensile stresses. Both modes of failure are influenced by *blank holder force* and *drawbead restraining force*. It result that why the most used manipulated process variables are blank holder force and drawbead restraining force. Many researchers identify the relationship between punch force and this two process variables in order to assure in-process control. Different methods - hydraulically controlled press [10-12], bi-directional force transducer [25] - are used to realize in-process control, based on tracking a *reference punch force trajectory*, by adjustment of blank holder force or drawbead penetration.

The ideal for in-process control is the measurement of stress and strain field throughout the sheet metal. Unfortunately, those measurements are impractical during the process. However, some displacements can be measured where sections of material remain free of surface pressure. Different solutions – mechanical and optical devices - to sense *draw-in of sheet metal* during the process are proposed: Hardt et al. [7] used linear variable differential transducers (LVDT's) to measure draw-in in order to control blank holder force during the forming process; Sunseri [34] and Siegert [32] also used an LVDT type draw-in sensor to reduce springback and wrinkling; Lo et al. [20] used a reflective photoelectric encoder to monitor the displacement of sheet metal blank; Doege et al. [5] developed a computer-mouse-like, ball sensor used to measure material draw-in direction, material flow velocity and material flow path in two orthogonal directions; those measurements are based on the mechanical transmission of the plane movement of the sheet metal onto a ball; Cao et al. [3, 4] developed a new type of draw-in sensor combining a LVDT with an optical sensor.

The *wrinkling* of sheet metal during forming process is common phenomenon appearing due to an excessive compressive stress. Detection and measurement of this process parameter are studied by many researchers. Pereira et al. [28] propose a method using two fibber optic displacement sensors for detecting low or high frequency wrinkling in sheet metal stamping process. The measurement of wrinkle height was achieved by Siegert et al. [32] by applying a combination of two opposing displacement transducers positioned in the upper binder and lower binder (Fig. 5).

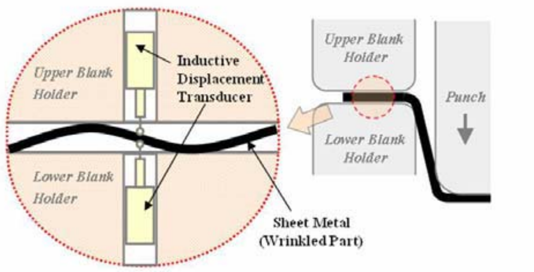

Fig. 5: Inductive displacement transducer for the measurement of the wrinkle height [32]

Unfortunately, changes in sheet thickness cause errors in the measurement of height of wrinkle and, additionally, this contact-based wrinkling sensor is limited in industrial application because of friction-based endurance failure.

However, all this in-process control solutions appears to be reasonable for overcoming such production challenges in sheet metal forming. Although some success in applying process control to sheet metal forming has reported, there are still many open problems like: *i)* systematic design of the process controller and reference trajectories; *ii)* inconsistency of machine control system when changes in lubrication and material properties occur; *iii)* sensing and actuation technologies not fully developed.

5. CONCLUSIONS

Improve significantly deep drawing process control requires: *i)* selection of the correct process variables in order to monitor real state of the material during the process and command the correction *ii)* generation of accurate reference trajectories for the process variables control using FEA and experiments; *iii)* reduce time consumption for deep drawing process and control system design; *iv)* combine different process control procedures and use those principal capabilities.

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