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Advances in the Control of Sheet Metal Forming

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Abstract: This paper presents a review of research on control of the sheet metal stamping process, and its effect on the quality of stamped parts. Section 1 of the paper introduces key quality considerations in the sheet metal stamping process, including new challenges for industrial needs. Section 2 presents the evolution of control strategies for the forming process. Section 3 describes the different types of active blank holder force (BHF) systems from previous research. Finally, Section 4 reviews in-process sensor technologies to monitor the process variables used in machine or process controllers for the sheet metal stamping process.

1. INTRODUCTION

1.1 Motivation

Sheet metal stamping is one of the primary manufacturing processes, because stamped parts can be produced with high speed and low cost for large volume production of components such as automotive body panels and fuel tanks. A stamped part is made by placing a sheet of metal between an upper die (or punch) and a lower die, which are geometric negatives of each other, and stamping the sheet of metal using a press. As shown in Fig.1, the basic components are a punch, die, and a set of blank holders which may, or may not, include drawbeads around the edges of the dies. The punch draws the blank sheet of metal to form the desired shape while the blank holder controls the flow of sheet metal into the die cavity.

The two main quality considerations in the sheet metal stamping process are formability (e.g., wrinkling caused by excessive local compression and tearing caused by excessive local tension) and dimensional accuracy (e.g., springback caused by elastic recovery), as shown in Fig 2. In addition, consistency, that is, minimizing dimensional variations (caused by lubrication, material properties, or thickness variations), is a key requirement in mass production.

New challenges arise from the use of new materials. For example, the need to reduce weight in automobiles, and to improve fuel economy, encourages manufacturers to choose lighter and stronger materials (e.g., aluminum and magnesium alloys) in place of steel. However, aluminum and magnesium alloys are not as formable as steel, and produce more springback and fracture problems (Adamson et al., 1996; Anon, 2006; Lee et al., 2007). Therefore, a major issue in manufacturing sheet metal products from such materials is the ability to consistently produce good parts, without tears, wrinkling, and minimal springback, using a given blank (with specified blank size, sheet thickness, and material properties) and tooling (with specified geometry).

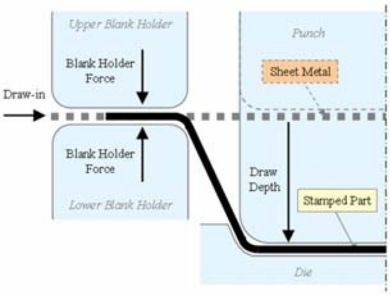

Fig. 1. Schematic of a sheet metal forming process

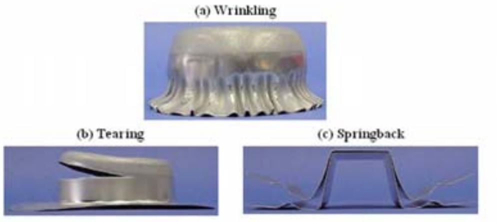

Fig. 2. Problems of part quality in the sheet metal forming process: (a) wrinkling, (b) tearing, and (c) springback

1.2 Background

To overcome production problems, tool and die manufacturers continuously integrate new techniques and ideas in sheet metal forming in their design. For example, using hydraulically-controlled actuators reduces die try-out time (e.g., grinding and welding the die) by controlling the flow of sheet metal via a controllable multi-cylinder blank holder actuator (Kergen et al., 1992; Siegert et al, 1998; Lo and Jeng, 1999; Hsu et al, 2002; Doege et al., 2003). In

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addition, researchers have developed different types of active blank holder systems (e.g., segmented/pulsating blank holder system and reconfigurable discrete die), to improve stamped part quality in forming (Michler et al., 1994; Walczyk and Hardt, 1998; Ziegler, 1999; Doege et al., 2001). Even though adjustable multi-cylinder blank holder systems contribute to improved quality of stamped parts and to reduced try-out times, the use of feedback control to eliminate the effects of disturbances, such as lubrication changes and material property variations, poses several technical challenges. Specifically, the in-process sensing of process variables (e.g., draw-in, punch force, and wrinkling) is an active area of research.

A recent review, specifically on controlling blank holder force (BHF) in stamping, discusses how part quality is affected by many variables including part geometry, blank material, surface finish, lubrication, and press characteristics (Ahmetoglu et al., 1992). They also concluded that the use of BHF control was critical for elimination of tearing and wrinkling. They also included a description for a specific machine control strategy of a hydraulically controlled multi-cylinder blank holder system.

In a review paper on control of manufacturing processes, Hardt (1993) discussed modeling and control methods in stamping from a control perspective, by comparing process objectives (e.g., quality, flexibility, and rate) and classical feedback system objectives (e.g., tracking disturbance rejection and stability). In particular, he pointed out that most efforts have focused on using existing methods on process independent problems, such as position control and trajectory following, thereby only indirectly influencing the actual process output. Thus, he presented methods for a more direct approach (e.g., deformation transfer function or discrete tooling concept) to process modeling and control.

Obermeyer et al. (1998) categorized technical papers which describe open- and closed-loop control of the BHF based on both experimentally and theoretically determined forming limit diagrams. Moreover, they reviewed how real-time control of the BHF has been expanded to include new approaches for controlling the flow of the sheet metal during the punch stroke.

Most recently, Cao et al. (2001) presented a summary of practical and theoretical challenges to the development and realization of stamping process controllers in terms of enhancing controllability and flexibility in next generation stamping systems. In addition, they discussed efforts to address material modeling, failure criteria, and process design and control.

1.3 Purpose and Scope

This paper presents a thorough review of developments in stamping process control, taking a broad view from conventional die try-out to in-process control in production. Section 2 presents an overview of stamping process control, including die try-out, machine control, in-process control, and cycle-to-cycle control. In Section 3, the development of different types of active BHF control systems is described to focus on their objectives and performance as well as their advantages and disadvantages in terms of complexity, applicability, and flexibility. Subsequently, Section 4 extensively reviews diverse sensors measuring stamping process variables in terms of their design and operation, including a description of their advantages and disadvantages with respect to complexity, applicability, and flexibility. Section 5 presents a summary and conclusions.

The main contributions of this paper are to:

- Review developments in forming control strategies and their impact (Section 2).

- Review adjustable BHF systems (Section 3).

- Describe sensors used to monitor process variables of the forming process (Section 4).

2. DEVELOPMENTS IN STAMPING CONTROL

Current research has focused on four possible ways to tackle the challenges in sheet metal forming. First, die try-out with open-loop control is a pre-process procedure to adjust tooling designs and process variables. Next, closed-loop machine control (see Fig. 3) is the on-line control of BHF based on finite element analysis (FEA) simulation or die-maker experience. Thirdly, in-process control (see Fig. 4) is an on-line strategy to apply feedback control to process inputs (e.g., BHF and drawbead restraining force) to mitigate the effect of disturbances during the forming process. Finally, cycle-to-cycle control (see Fig. 5) is based on post-process part inspection to determine critical process variables to be monitored.

2.1 Die Try-out

Die try-out determines the parameters (such as die geometry and BHF) that control the forming process to avoid tearing and wrinkling by physical modifications (e.g., grinding and welding) of the die surface and alteration of the BHF in sheet metal stamping. The die try-out procedure is time-consuming, with many cycles of trial and error. Sklad and Harris (1991) noted that most changes in stamping are connected with altering die geometry data (e.g., binder geometry and drawbeads), because part geometry data and material data are normally fixed in the stamping process. They also noted that a poorly-tuned open-loop forming process, which is close to failure, can result in frequent disruptions in manufacturing scheduling and a high scrap rate, and significantly increase costs. Therefore, Finite Element Method (FEM) software tools play an important role in rapid evaluation of forming severity, with respect to fracture and wrinkling, prior to actual die manufacturing in order to reduce costs and scrap rate.

Although die try-out is costly and time-consuming, many techniques have been incorporated in die try-out, and lead time and production costs have been improved. Herderich (1990) has developed empirical equations to predict the force necessary to form sheet metal around drawbeads. He suggested useful concepts in determining BHF and the number of nitrogen gas cylinders and/or nitrogen gas pressures with respect to quality of stamped parts. Xu and Zhao (2007) discussed the reduction of springback through open-loop compensation of mechanics-based springback reduction (e.g., drawbead constraint force) and geometry-based springback reduction (e.g., die face compensation). Zhang et al. (2007) described technical challenges in applications and impact of open-loop line die forming simulation on die development.

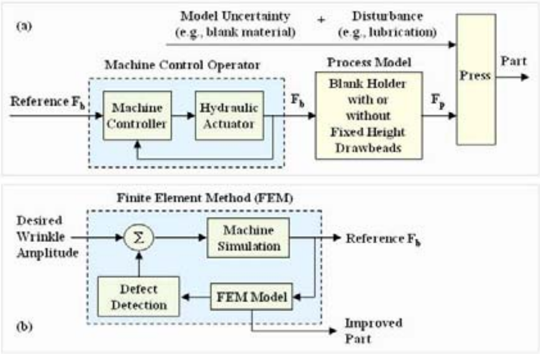


Fig. 3. Closed-loop machine control: (a) adjust the BHF to achieve the reference BHF (b) determination of the BHF profile using FEM analysis

2.2 Closed-Loop Machine Control

The closed-loop machine control strategy, as illustrated in Fig. 3, is to control the BHF, F_b, to follow a predetermined reference trajectory. Closed-loop machine control requires a predetermined reference BHF trajectory that can be obtained through experiment and/or FEM simulation. The reference BHF depends on its location on the die and is a function of the punch stroke. The punch force (F_P), as shown in Fig. 3, is an output of the process and is directly associated with fracture and wrinkling. F_p is affected by the BHF. Thus, the relationship between the punch force and the BHF, obtained using mathematical modeling and/or experiments, can be used to design a process controller which generates a reference BHF trajectory for the machine controller.

Experimentally, different kinds of BHF trajectories (e.g., a step change in the BHF) have been used to study their effects on produced part quality. Some of them have been demonstrated to improve formability (Ahmetoglu et al., 1992; Kergen and Jodogne, 1992; Ziegler, 1999), to reduce springback (Adamson et al., 1996; Sunseri and Cao, 1996; Siegert, 1992, 1997; Ziegler, 1999), and to improve part consistency (Adamson et al., 1996). However, these investigations have not led to methods to determine BHF trajectories to make good parts.

Kergen and Jodogne (1992), however, showed how to experimentally design a minimum BHF trajectory and a maximum one using closed-loop machine control based on wrinkle detection. However, the measured BHF trajectories, and the minimum BHF obtained from experiments varied significantly with the properties of the steels used in the experiments. The initial BHF values used by the authors were high, from which point the closed-loop control began to decrease the BHF, as the punch load increased, in order to ensure that the material is stretched to the highest level without causing tearing. The minimum BHF value corresponded to approximately the same point in the punch stroke as the maximum punch force. The authors found such a scheme yields improvements in the achievable limiting draw ratios.

Sunseri et al. (1996) showed how to determine the variable BHF reference trajectories by both finite element simulation and experiments, for winkling and tearing control. They monitored punch force history during the process, if the punch force history derivated from the target punch force trajectory, a proportional-integral (PI) controller acted to change the BHF during the stamping process in order to maintain the desired target punch force history based on the amounts of draw-in and thickness distribution of sheet metal. A FEM of the forming process was used to simulate the same controlled process. The corresponding BHF histories were obtained for different friction cases, in order to maintain the desired punch force.

Sheng et al. (2004) and Zhong-qin et al. (2007) predicted the optimal magnitude of the BHF to improve fracture and wrinkling problems in deep drawing. They used FEM simulation of closed-loop control based on the wrinkling and fracture detection of sheet metal. They showed the variable BHF profile predicted by adaptive FEM simulation, and compared the optimum constant BHF profile (see Fig. 3b). Using a pre-determined variable BHF profile, they formed a cup to a depth of 47mm without any failures. Compared with a cup formed by optimum constant BHF, this represented an increase of 9% in cup depth. Optimal trajectories of variable BHF by FEM simulation were developed in (Zhong-qin et al., 2007), and shown with a PID closed-loop controller to increase the forming limit by 30% (i.e., from 45mm to 60mm forming depth) compared to constant BHF.

The main disadvantage of closed-loop machine control is that it cannot eliminate the influence of disturbances (e.g., variations in lubrication and blank thickness) on part quality and consistency. For example, two tests were conducted using closed-loop machine control with a predetermined BHF trajectory but with different lubrication conditions. Results showed that there were differences in part quality but not in BHF for the two tests (Hsu et al., 2000).

2.3. In-Process Control

In-process control is used to control a measurable process variable (e.g., punch force or draw-in) to follow a reference trajectory by manipulating the BHF (see Fig. 4). To implement the in-process control, a process controller and reference trajectory are needed after the monitored process variable is selected, in addition to the machine control scheme shown in Fig. 3.

Hardt and Fenn (1993) performed a series of constant BHF experiments to find failure height and then defined optimal tangential force (i.e., punch force) and normalized average thickness trajectories as the actual trajectories of these variables when the failure height was the largest. Then, they presented a method for in-process control of the BHF to ensure optimal forming conditions based on desired optimal trajectories. The method was implemented using closed-loop control based on process variable feedback, and subjected to experiments where various disturbances (e.g., lubrication and material change) were considered.

Siegert et al. (1997) showed that the material flow is highly dependent on the friction force between the sheet metal and the upper and lower binder. They introduced process control using friction force as the controlled variable to avoid wrinkling and tearing during the stamping process. They also showed that the actual friction force follows the desired nominal curve of BHF. Therefore, they focused on monitoring the friction force by using a sensor, and utilized feedback control to realize the desired friction force curve over the stroke.

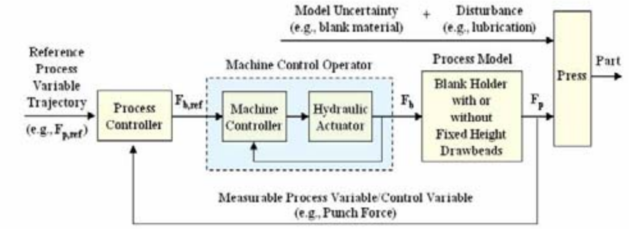
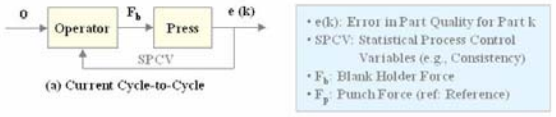


Fig.4. In-process control of sheet metal forming process with reference punch force trajectory

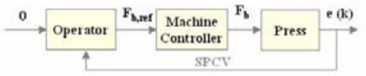
Bohn et al. (1998) developed a new multiple-point active drawbead forming die to improve part quality, using drawbead restraining force based on measuring the die shoulder force during the drawing process. In comparison to their previous work (Michler et al., 1994), they expanded the study to include multiple-point actuation with closed-loop control and developed second-order transfer functions for modeling the drawbead hydraulic actuators. They also monitored punch stretching force and adjusted the displacement of the active drawbead to constrain material flow, thus, avoiding tearing and wrinkling during the forming process.

Hsu et al. (2000 and 2002) demonstrated that in-process control can be used to improve stamped part quality and consistency of a simple part by adjusting the BHF in forming based on tracking an optimal punch force trajectory. They pointed out that a process controller and reference punch force trajectory had to be included in the design (see Fig. 4). In particular, their approach included modeling of the sheet metal forming process, design of the process controller, and determination of the optimal punch force trajectory. They achieved good results using a proportional-integral controller with feedforward action (PIF) process controller in both simulation and experiments.

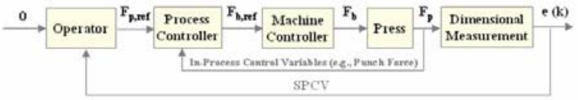
Kinsey et al. (2000) proposed a neural-network system, along with a stepped BHF trajectory, that was able to control springback in forming. A neural network was chosen due to its ability to handle the highly non-linear coupled effects that are found in sheet metal forming when variations in material and process parameters occur. Polynomial coefficients from curve fitting of the punch force trajectory were used as inputs into the neural network. Viswanathan et al. (2003) experimentally implemented the neural-network based process control for springback reduction during forming. They noted that neural-network control would be effective in dealing with material variations. However, for forming a complex part, they noted that more advanced sensors (e.g., local draw-in or local tangential force measurement) are needed because punch force alone is not sufficient in identifying variations.



(a) Current Cycle-to-Cycle



(b) Better Cycle-to-Cycle with Machine Controller



(c) Best Cycle-to-Cycle with Process Controller

Fig. 5. Expected evolution of cycle-to-cycle control, (a) current, (b) with machine control, and (c) with in-process and machine control

Recently, Doege et al. (2003) described a new optical draw-in sensor for in-process material flow measurement and its application for closed loop process control in the sheet metal forming. They developed a press with a multi-point draw-in measurement tool within the control loop. They produced locally varying forces on the blank holder, in accordance with material flow information. Draw-in velocity along the drawing depth was controlled in accordance with desired BHF to produce parts without wrinkling and tearing.

Machine control can suffer from inconsistency when changes in lubrication and material properties occur. Thus, in-process control appears to be a reasonable solution for overcoming such production challenges in sheet metal forming. Although some success in applying process control to sheet metal forming has been reported, there are still many open questions. For example, the systematic design of the process controller and reference trajectory in forming process are not well addressed and sensing and actuation technologies are not fully developed.

2.4 Cycle-to-Cycle Control

Statistical process control methods are used to implement cycle-to-cycle control based on the dimensional measurements of stamped parts. In cycle-to-cycle control, an important aspect is to maintain a database of process variables (e.g., material property, lubrication, BHF, punch force, draw-in, and punch speed). For example, as illustrated in Fig. 5, operator experience is necessary to adjust a process variable(s) at each cycle. Ultimately, the current cycle-to-cycle control, where an operator closes the loop using dimensional measurement in an otherwise open-loop process, could be improved when combined with machine control and in-process scheme.

Manabe et al. (1999) proposed the use of a database for an intelligent sheet metal forming system to enable design of a process control system without experts who are skilled and experienced in the forming process. They developed a fuzzy rule model which provides an easy way to optimize cycle-to-cycle control, because the deep drawing process is not only unsteady and complicated but has nonlinear characteristics. Their method resulted in around 25% reduction in production time. They were able to increase the draw-depth of an experimental cup by 0.77mm using their method.

Hardt and Siu (2002) proposed a single-input, single-output (SISO) control scheme based on output measurement and input change after each processing cycle. They also experimentally implemented cycle-to-cycle control of a simple bending process. Rzepniewski and Hardt (2003 and 2005) provided the extension of the cycle-to-cycle control concept to the general Multiple-Input Multiple-Output (MIMO) situation. It has been shown that properties of zero mean error and bounded variance amplification that were seen for the SISO case can also be achieved for the MIMO case. Finally, they noted that MIMO cycle-to-cycle control is an appropriate candidate for a system having many thousands of inputs and outputs (e.g., reconfigurable discrete forming die, see Section 3.5).

Cycle-to-cycle control itself has been used to improve stamped part quality through post-process inspection or in-process variable monitoring. However, post-process corrections can only be achieved after bad parts are produced. Ultimately, in-process control, despite its additional cost and difficulty in sensing, is needed to improve formability, dimension accuracy, and consistency in production.

3. ACTIVE BINDER CONTROL SYSTEMS

In the sheet metal stamping process, the BHF controls the material flow into the die cavity, and optimal material flow plays a critical role in producing a good stamped part. Conventional passive die-cushions filled with nitrogen gas could be replaced with an active BHF control system actuated by multiple hydraulic cylinders. The objective is to improve the formability and dimensional accuracy of stamped part by varying the BHF at different locations on the die, as well as at different times during the punch stroke.

Our recent research shows that die try-out time can be reduced by up to 80% when an active binder system, controlled by multi-cylinder actuators, is used in die try-out. This is accomplished by varying the BHF at different locations based on punch stroke, instead of grinding and welding.

3.1 Segmented Blank Holder System

While the elastic binder (Doege et al., 2001) focused on generating homogeneous binder pressure on the blank of the sheet metal, a segmented blank holder (or flexible binder) is able to accomplish control of one segment while not being significantly influenced by the variation and distribution of other segments.

Yagami et al. (2004) employed segmented blank holder modules to control the material flow into the die cavity, enhancing the effect of the BHF control and improving formability in the stamping process. They obtained fuzzy blank holder pressure (BHP) trajectories for each blank holder segment and showed that the distributed BHP method can improve wall thickness distribution.

Recently, Wang et al. (2005) developed a space variant BHF system with segmented blank holders 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.

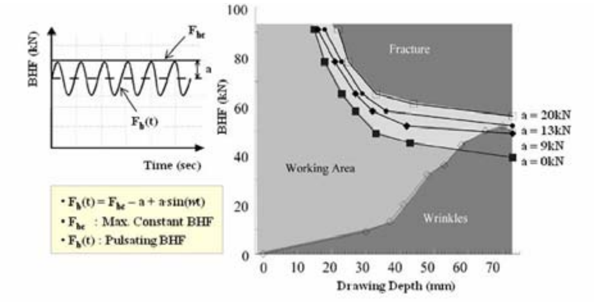


Fig. 6. Working area for pulsating BHF with amplitudes of 0kN (static case), 9kN, 13kN, 20kN; frequency: 3Hz; sheet material: ZEPH (Ziegler, 1999)

3.2 Pulsating BHF Control System

A new approach to the variation of BHF has involved pulsation. Experiments by Ziegler et al. (1999) showed 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 (see Fig. 6). The reduction in the friction force achieved when the pulse reduces the BHF to below this maximum allows increased deformation to occur prior to tearing, without sacrificing effective wrinkle suppression. An example of the increase in the working window achieved with zinc-coated and phosphated steel sheets, employing a pulse frequency of approximately 3 Hz (the specific frequency itself was determined to be of little influence), is demonstrated in Fig. 6. The key objective that he tried to achieve was to avoid cracks on the surface by reducing the friction force. For example, with constant BHF, it was only possible to avoid cracks for the friction coefficient $\mu = 0.1$. With higher friction coefficients cracks occur. With pulsating BHF, it was possible to avoid cracks even if the friction coefficient increased up to $\mu = 0.12$. Ultimately, this showed that pulsating BHF helped to increase the robustness of the process and contributed to avoiding scratches on the surface of stamped parts. However, the amplitude and frequency of the pulses would need to be tuned with respect to the lubrication and material properties for a given stamping.

3.4 Active Drawbead Control System

Material flow in the forming process is often modified locally by the insertion of drawbeads into the tooling. In practice, the drawbead is a fixed component on the dies. However, Michler et al. (1994) and Bohn et al. (1998) implemented their control function with a set of active drawbead actuators. They constructed a multiple-action hydraulic sheet metal strip-drawing tool for the purpose of studying the effectiveness of feedback control in forming. As shown in Fig. 7, a punch pulls a strip of sheet metal over a die shoulder and a controllable drawbead is located in the center of the blank holder. Both drawbead penetration and BHF are controlled while the apparatus is measuring and recording the drawbead position, the vertical drawbead force, BHF, and the punch (strip pulling) force (i.e., measured output). In experiments, a PI controller was used, adjusting the drawbead penetration to compensate for the deviation between the reference input (i.e., desired punch force trajectory) and the measured output (i.e., actual punch force).

An active drawbead control system can achieve fast response and require smaller energy consumption than other types of active blank holder systems consisting of large inertia-based hydraulic actuators. However, this idea is difficult to implement in practice, due to complexity and cost in the production of the dies.

3.5 Reconfigurable Discrete Die

A reconfigurable forming tool attempts to use a die whose shape can be rapidly reprogrammed between forming cycles. If the die surface is in some way programmable, then, the stamped part quality can be improved. Obviously, a key advantage of the reconfigurable die is that it rapidly enables one to regenerate new dies, whose shape is different from previous ones, with aid of die reconfiguration actuators.

Walczyk et al. (1998) and Hardt (2002) addressed the design and analysis issues involved with movable die pins, turning a matrix of die pins into a rigid tool, and the pin matrix containment frame. As illustrated in Fig. 8, they proposed a feedback control scheme to monitor directly the 3D shape of the stamped part. Using this approach, the pin actuators are controlled by the shape controller until part shape errors are minimized with respect to a predetermined shape trajectory. The reconfigurable tool was combined with a three-dimensional shape-sensing device and a spatial frequency-based control law. However, the reconfigurable discrete die may not be applicable to produce very complex part shapes. Challenges include optimizing the number of actuator pins with respect to cost and mechanical complexity.

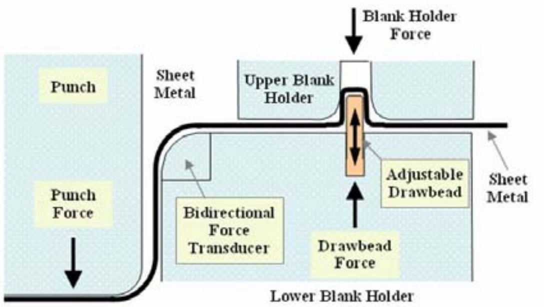


Fig. 7. Schematic diagram of the active drawbead control system with bidirectional transducer (Michler et al., 1993)

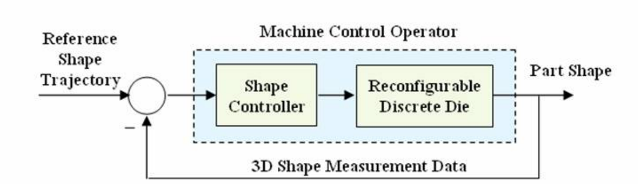


Fig. 8. Shape control system using a reconfigurable tool and spatial frequency controller (Hardt, 2002)

4. PROCESS VARIABLES AND SENSORS

There are many opportunities to measure physical quantities either on the machine or the workpiece itself in stamping. Because the most important constitutive relationship for forming is stress-strain or force-displacement, the latter two quantities are most often measured. In general, monitoring process variables (e.g., punch force, draw-in, and wrinkling) in the sheet metal forming process is very important to improve stamped part quality and to reduce cost and time-consuming die-work. Thus, many researchers have focused on sensors to monitor process variables for use in control of the stamping process.

4.1 Punch Force

Among the process variables, punch (i.e., strip pulling) force is valuable to interpret the stress-strain curve for the material, because sheet metal pulling force is directly involved in failure (Hosford et al., 1993). The punch force can be measured using commercial sensors installed on the stamping press.

Michler et al. (1994) detected the punch force using a bi-directional force transducer for an adjustable drawbead system that varied drawbead penetration to control the draw-in restraining force. This behavior of the punch force is influenced to a significant extent by the drawbead restraining force.

Similar measurement of the punch force was achieved by Hsu et al. (1999, 2000, and 2002) They presented in-process control though adjustment of the BHF using a hydraulically controlled press based on tracking a reference punch force trajectory to improve part quality and consistency.

Sensing the punch force as a process variable in the forming process is easy to implement in practice. However, the measured punch force represents the resultant effect of the forming process and lacks local detail.

4.2 Draw-in

The ideal feedback measurement for in-process control of forming would be the stress and strain field throughout the sheet metal. With this information local springback can be reduced and fracture can be also prevented. Unfortunately, in-process measurements of stresses and strains are impractical. However, certain displacements can be measured. In processes where sections of material remain free of surface pressure, mechanical and optical measurement devices could be inserted to sense draw-in of the sheet metal.

Using linear variable differential transducers (LVDTs), Hardt et al. (1993) measured draw-in to control the BHF in process to ensure optimal forming conditions. Then, they proved that displacement of the edge of the sheet during draw-in was not reliable because of tearing. They also proposed a method that measured the circumferential contraction of the material, in averaging all draw-in over the entire circumference of the blank.

Sunseri et al. (1996) and Siegert et al. (1997) also used an LVDT type draw-in sensor to reduce springback and wrinkling respectively. However, the LVDT requires significant setup time in practice, and becomes too time-consuming and expensive to use in production.

A compact, economic draw-in sensor to overcome the week-point of the LVDT type sensor has been developed. Lo et al. (1999) monitored the displacement of sheet metal blank, using a reflective photoelectric encoder, which has a rotating wheel where it contacts the sheet metal. However, this sensor can detect only one direction as the sheet metal moves tangentially with respect to the rotating wheel.

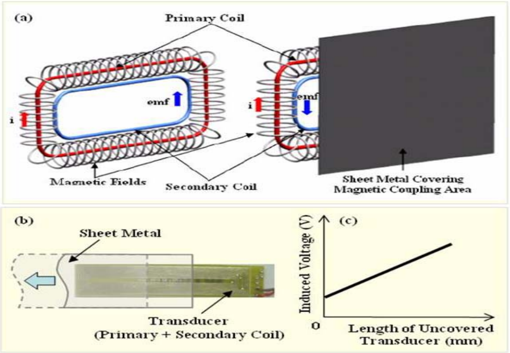


Fig. 9. (a) Operating principle of transducer (b) transducer and sheet metal configuration (c) Induced voltage signal from transducer (Cao et al., 2002; Mahayotsanun et al., 2005)

Doege et al. (2002) developed a computer-mouse-like, ball sensor which is based on the mechanical transmission of the plane movement of the sheet metal onto a ball. Using the ball sensor the material draw-in direction, material flow velocity and material flow path can be independently measured in two orthogonal directions. Doege et al. (2003) also designed a computer-mouse-like, contactless-optical sensor for online sheet metal flow measurement. This contactless-optical sensor consists of a chip in which a complementary metal oxide semiconductor (CMOS) sensor and a digital signal processor (DSP) are integrated. One point from the sheet surface is analyzed by the sensor and described at its initial position by the two pixel values (i.e., P_{X1} and P_{Y1}). When the object is moved, the image point moves to a different position with the pixel values (i.e., P_{X2} and P_{Y2}). Sensing accuracy of optical sensors in draw-in displacement was improved at each local position, compared to the contact-based draw-in sensor. However, on the lower stamping die there are still implementation difficulties and cost challenges for practical use.

Cao et al. (2002 and 2005) developed a new type of draw-in sensor which has two key advantages: ease of setup and cost-effective implementation in industrial applications. The installation of LVDT and optical sensors requires either setup time with each forming cycle or intricate tooling modification. Based on the mutual inductance principle, they designed a draw-in sensor by experimenting with a prototype printed on a conventional circuit board to address the need for an affordable and accurate draw-in sensor. This design of sensor was small enough to be embedded in a die or blank holder. In the single transducer configuration the primary and secondary coils, as shown in Fig. 9a, were printed into one transducer board. Utilizing the principle of mutual inductance between the two loops, the linear draw-in of sheet metal was detected based on the uncovered area of the primary and secondary coils on the board, as seen in Fig. 9b. The linear position sensor transmitted signals to a signal conditioning board, which amplified and filtered the induced voltage readings and these readings were sampled using a computer based data acquisition system. Thus, sheet metal draw-in can be obtained using the voltages generated by the draw-in sensor, after calibration using an LVDT, as illustrated in Fig. 9c. However, the sensor has to be calibrated for each material used and the inductive characteristics are dependent on material properties. Consequently, if this sensor is able to demonstrate endurance for a large number of stamping cycles, it may become adopted by industry due to its ease of use and low cost. In particular, thick epoxy (i.e., about 0.8~2mm) covers the top of the sensor to protect it from wearing out over many hours operation and to place constant gap between the transducer and the sheet metal. However, it may have errors due to wrinkling, which creates varying gap conditions between the transducer and the blank.

4.3 Wrinkling

The wrinkling of sheet metal is a common phenomenon which arises in forming due to compressive stresses. The ability to sense the occurrence of wrinkles is potentially useful in the sheet metal forming process consisting of closed-loop process control systems (e.g., active BHF).

Pereira et al. (1994) presented a method using two fiber optic displacement sensors for detecting low and high frequency wrinkling in stamping. From two parallel non-contact readings attached to the upper binder, estimation of the peak amplitude of the wrinkle was achieved by combining estimation of wrinkle frequency (ω) with the distance between two sensors. Though this non-contact based optical wrinkle sensor would be free from the wear problem in applications, it has also a technical challenge; it is difficult to choose the optimal distance between two readings based on the smallest wrinkling frequency in order to avoid aliasing (e.g., 2 or more oscillations of wrinkling within the distance between two readings).

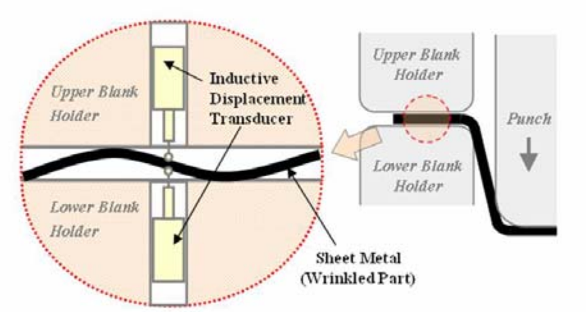


Fig. 10. A schematic of inductive displacement transducer for the measurement of the wrinkle height (Siegert et al., 1997)

The measurement of wrinkle height, as shown in Fig. 10, was achieved in closed-loop stamping by applying a combination of two opposing displacement transducers, which are positioned in the upper binder and the lower binder (Siegert et al., 1997). The displacements of the two transducers can be used to measure the real wrinkle height. Changes in sheet thickness cause errors in the measurement of the height if only the displacement between upper and lower binder is measured. However, this contact-based wrinkling sensor is limited in industrial application because of friction-based endurance failures at the sensor tip that contacts the sheet, and also because wrinkle locations are not known a priori.

5. CONCLUSIONS

This paper reviews key developments in feedback control of the sheet metal stamping process and its effect on the quality of stamped parts. The use of feedback control to improve part quality requires addressing several technical issues, including the generation of accurate reference trajectories for the control loops using FEM or design-of-experiments. In-process control also requires the implementation of controllers to adjust BHF and achieves the control objective of tracking the desired reference trajectories. The design of these controllers requires accurate models of the forming process. In addition, the development of reliable, cost-effective sensors to measure representative process variables is also a key technical challenge. Addressing these issues will lead to the creation of systems that combine statistical process control methods, machine control, in-process control, and cycle-to-cycle control capabilities to significantly improve part quality and consistency in the stamping process.

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