An Approach for Modeling Sheet Metal Forming for Process Controller Design

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Varying the blank holder force during forming can lead to higher formability and accuracy, and better part consistency. Process control, using on-line adjustment of the blank holder force to follow a reference process variable (e.g., the punch force, the draw-in, etc.) trajectory has been applied to sheet metal forming. However, process controller design has not been thoroughly addressed. In this paper, the essential part for systematic process controller design, i.e., modeling a sheet metal forming process, will be addressed in terms of control terminology (e.g., the process model, the model uncertainty and the disturbance). A process model for u-channel forming, i.e., a mathematical relationship between the blank holder force and the punch force, is presented and experimentally validated. Characterization of the model uncertainty mainly due to small variations in blank size, sheet thickness, material properties and tooling shape due to die wear and the disturbance which is mainly due to friction is developed. [S1087-1357(00)01304-6]

1 Introduction

1.1 Challenges in Sheet Metal Forming. Sheet metal stamping is an important manufacturing process because of its high speed and low cost for mass production. Figure 1 shows a schematic of a simplified stamping process. The basic components are a punch, and a set of blank holders which may include drawbeads. The punch draws the blank to form the shape while the blank holder controls the flow of metal into the die cavity. Some process variables are also shown: F_p is the punch force, F_b is the blank holder force, and F_r is the restraining force within the blank.

The quality of stamped parts is critical to avoiding problems in assembly and in the final product performance. Two main considerations regarding the quality of stamped parts are formability (e.g., wrinkling caused by excessive compression and tearing caused by excessive tension) and dimensional accuracy (e.g., springback caused by elastic recovery). In addition, consistency (e.g., dimensional variations caused by lubrication or thickness variations) in the stamping process significantly affects subsequent assembly in mass production.

New challenges emerge from the use of new materials. For example, the urgency for reduction of automobile weight to improve fuel economy forces manufacturing companies to choose lighter materials (e.g., aluminum) in place of steel. However, aluminum is not as formable as steel and produces more springback [1,2]. Therefore, a major issue in manufacturing sheet metal components is the ability to consistently produce good parts (e.g., no tearing, no wrinkling, and minimum spring-back) from a given material (i.e., blank size, sheet thickness, and material properties) and tooling (i.e., tooling shape).

1.2 Control of Material Flow. The control of flow of material into the die cavity is crucial to good part quality and consistency, and the blank holder with or without drawbeads is used to control the material flow. Two techniques to control material flow have been investigated. One is by manipulating the blank holder force during forming in a flat binder or in one with fixed height drawbeads. The other is by controlling the drawbead penetration which can be adjusted during forming.

It is worth pointing out that mechanical presses are being retrofitted with hydraulic cushions to give the presses additional flexibility compared with those equipped with pneumatic or nitro-activated cushions. Hydraulic cushions give operators more capability to control the blank holder force.

A press with hydraulically computer-controlled blank holder is capable of controlling the binder force to track a predetermined variable blank holder force trajectory during forming. This type of control is referred to as ''open-loop'' or ''machine'' control. Previous research showed that this kind of control can improve material formability [3–6], reduce springback [1,2,7–12], and improve part consistency [1,2]. However, for a given material (i.e., blank size, sheet thickness, and material properties) and tooling (i.e., tooling shape), machine control cannot maintain its performance with regard to changes in lubrication [13,14].

1.3 Process Control in Sheet Metal Forming. Presses with machine control can be converted to ones with ''closed-loop'' or ''process'' control. Figure 2 shows a block diagram of process control for sheet metal forming. In this figure, a measurable process variable or control variable (e.g., the punch force) is made to follow a reference trajectory (e.g., a reference punch force-displacement trajectory) through manipulation of the blank holder force. The process controller is designed to automatically generate the necessary blank holder force command (i.e., F_{bc}) for the machine controller to keep the difference between the measured and the reference process variable as small as possible. Using feedback control for process controller design reproduces the reference process variable trajectory and reduces the sensitivity to variations in system characteristics (e.g., lubrication). Note that separation of the process controller and the machine controller

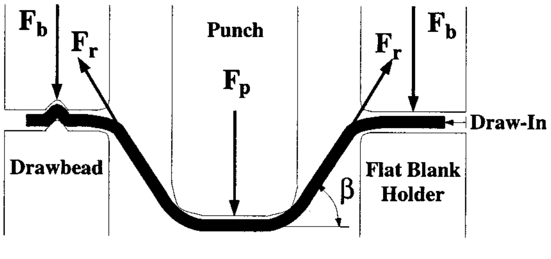

Fig. 1 Schematic of a stamping process

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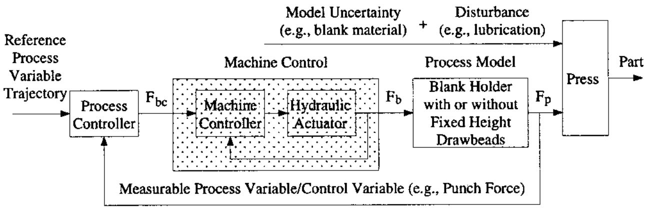

Fig. 2 Process control of sheet metal forming

may not be necessary and that the command generated by the process controller depends on how the block diagram is constructed. Hardt and Fenn [13] have applied process control, using either a previously determined optimal punch force trajectory or a normalized average thickness trajectory as the reference process variable trajectory, to cup forming. They showed that this strategy could produce cups with ''optimal'' height regardless of initial binder force and friction conditions. Sim and Boyce [15] investigated the same problem using finite element analysis. A similar approach using the draw-in as the control variable has been reported by Siegert et al. [16], Siegert et al. [17], and Sunseri et al. [10]. Another similar approach using the friction force as the control variable has been investigated by Siegert et al. [18].

Controlling the drawbead penetration has also been applied to sheet metal forming. The steady state relationship between the drawbead penetration, i.e., an alternate way to control material flow, and the drawbead restraining force was investigated by Demeri [19]. The dynamic relationship between the drawbead penetration and the drawbead restraining force, the so called ''open-loop'' control, has been reported by Cao and Boyce [20], Michler et al. [21], and Hao et al. [22]. ''Closed-loop'' control, to manipulate the drawbead penetration by making the punch force track a reference trajectory, has also been studied by Cao and Boyce [20], Michler et al. [21], and Hao et al. [22]. Although this paper focuses on controlling the blank holder force as the mechanism to control the material flow into the die cavity, the drawbead penetration can also be used to realize similar effects.

To successfully implement process control in sheet metal forming, two key issues, namely, process controller design and the reference process variable trajectory, must be addressed. For a given material (i.e., blank size, sheet thickness, and material properties) and tooling (i.e., part shape) but a different lubrication, consistency of part quality can be related to consistency in the measured punch force trajectory. Consistency can be improved through the tracking performance of process control using a reference punch force trajectory [14]. At the same time, part quality can be related to an optimal reference punch force trajectory. Better part quality can be achieved through selection of the reference punch force trajectory using a good process controller [14]. The tracking performance of process control is important to part consistency and part quality. Therefore, process controller design must achieve a high tracking performance regardless of lubrication and small variations in blank size, sheet thickness, material properties and tooling.

1.4 Process Controller Design. In terms of control terminology, the closed-loop system, including the process model and the process controller, must have high performance of tracking the reference punch force trajectory through manipulation of the blank holder force regardless of the disturbance and the model uncertainty. To systematically develop a good process controller, two tasks must be performed. One task is modeling sheet metal forming in terms of process model, model uncertainty, and process disturbance. For a given material (i.e., blank size, sheet thickness, and material properties) and tooling (i.e., part shape), a process model (i.e., a mathematic relation) should be able to describe the characteristic relationship between the blank holder force and the punch force. Model uncertainty would include small variations within the forming system such as small variations in blank size, sheet thickness, material properties, and tooling, while process disturbance would include external input to the forming system such as lubrication. The other task is to develop a controller with high tracking performance through available controller design techniques.

This paper deals with modeling sheet metal forming in terms of the process model, the model uncertainty, and the disturbance. *U*-channel forming is used to demonstrate the approach.

1.5 Background in Modeling Sheet Metal Forming. Issues in modeling for control of sheet metal forming have not been properly addressed, especially, from a control point of view. A useful process model must satisfy two requirements:

1 The process model must be as simple as possible to simplify process controller design.

2 The process model must be accurate enough to capture the characteristic relationship between the blank holder force and the punch force. This requirement is necessary for computer simulation to evaluate the performance of a designed process controller.

Most sheet metal forming models (i.e., the block for ''Blank Holder with or without Fixed Height Drawbeads'' in Fig. 2) are based on finite element analysis, which are very complex and, therefore, are not suitable for controller design. Majlessi et al. [23] developed a piecewise linear model for controller design. Their model, however, cannot be used in closed-loop simulation, because it cannot capture changes in process dynamics with respect to changes in the blank holder force.

Characterization of the process model uncertainty and the disturbance which are related to lubrication and small variation in blank size, sheet thickness, material properties and tooling has not been investigated.

1.6 Objective. The purpose of this investigation is to develop an approach for modeling sheet metal forming processes in order to lay the foundation for systematic design of appropriate process controllers. Modeling sheet metal forming includes process modeling and developing model uncertainty and process disturbance. The process model describes the mathematical relationship between the blank holder force and the punch force. The model uncertainty and process disturbance are related to different lubrication and small variation in blank size, sheet thickness, material properties and tooling shape due to die wear.

In this paper, *u*-channel forming is used to demonstrate the approach. The punch force is used as the measurable process variable, and the blank holder force is used to control the material flow.

The process variable chosen (i.e., the punch force) for process control may not be as good as other process variables (e.g., the draw-in, the friction force, and the thickness). However, the punch force is easier to measure and monitor with existing facilities. Moreover, since the main interest is to develop a methodology for process control, choosing the type of a process variable is not critical at this stage.

The derivation of the process model is based on observations of the measured punch force trajectories for constant blank holder force tests and step-change blank holder force tests for *u*-channel forming [24]. The process model will be validated through comparison of predicted and measured punch force trajectories for step-change and continuously varying blank holder force trajectories.

2 Modeling of Sheet Metal Forming

For the stamping process in Fig. 1 with the given lubrication, blank size, sheet thickness, material properties and tooling, the manipulated input is F_b, the controlled (measured) output is F_p, and the process model describes the characteristic relationship between them. The variation of the friction force due to the variation of the friction coefficient or lubrication is assumed to be a distur-

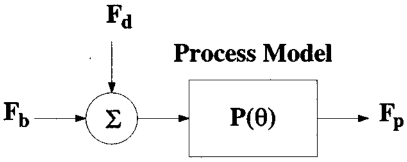

Fig. 3 Block diagram of the sheet metal forming model

bance, because it can be specified in terms of the variation of F_b, which will be shown later. Figure 3 shows the block diagram of the model of sheet metal forming where F_d is the disturbance, $P(\theta)$ is the process model, and θ is the model parameter related to blank size, sheet thickness, material properties and tooling.

2.1 Process Model. A process model describes the mathematical relationship between F_b and F_p. It is derived by assuming that the punch force, F_p, is a function of the blank holder force, F_b, and time, t.

$$F_p=F_p(F_b,t) \tag{1}$$

Because punch velocity (v_p) is constant, t can be used instead of the punch displacement, x_p (i.e., $x_p=v_p\cdot t$). Differentiating Eq. (1) with respect to time leads to a dynamic relationship between F_p and F_b.

$$\dot{F}_p=\frac{\partial F_p}{\partial t}+\frac{\partial F_p}{\partial F_b}\dot{F}_b \tag{2}$$

Experimental results for u-channel forming [1,24] at constant blank holder force showed that the relationship between F_b and F_p was similar to a first order system response for a step input. Hence, for each constant value of F_b, the dynamic behavior of F_p can be approximated by

$$\dot{F}_p\simeq-\frac{1}{\tau}F_p+\frac{\alpha}{\tau}F_b \tag{3}$$

where α is the DC gain and τ is the time constant. Both α and τ change when different values of F_b are used.

In Eq. (2), $\dot{F}_b=0$ when F_b is constant. Therefore, combining Eqs. (2) and (3) yields:

$$\frac{\partial F_p}{\partial t}\simeq-\frac{1}{\tau(F_b)}F_p+\frac{\alpha(F_b)}{\tau(F_b)}F_b \tag{4}$$

where $\alpha(F_b)$ is the DC gain and $\tau(F_b)$ is the time constant. Note that both are assumed to be functions of the constant value of F_b. Therefore, substituting Eq. (4) into Eq. (2) leads to, for constant blank holder force ($\dot{F}_b=0$),

$$\dot{F}_p=-\frac{1}{\tau(F_b)}F_p+\frac{\alpha(F_b)}{\tau(F_b)}F_b \tag{5}$$

The predicted punch force response to constant blank holder force can be obtained by solving Eq. (5)

$$F_{pc}=\alpha(F_b)\cdot F_b\cdot\left(1-\exp\left(-\frac{t}{\tau(F_b)}\right)\right) \tag{6}$$

Experimental results for u-channel forming [1,24] at blank holder forces with a step change showed an abrupt change in the punch force when a step change in the blank holder force occurred. The trend is schematically shown in Fig. 4. A mathematical relationship describing this response is given by:

$$F_p=\begin{cases}F_{pc1}(F_{b1},t), & 0\leq t<t_s\\ F_{pc2}(F_{b2},t), & t_s\leq t<t_f\end{cases} \tag{7}$$

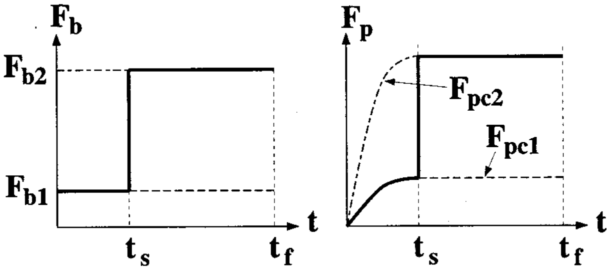

Fig. 4 Schematic response of F_p to F_b with a step change

When F_b changes from F_{b1} to F_{b2} at t_s, F_p changes from F_{pc1} to F_{pc2}. Note that F_{pc1} and F_{pc2} are the theoretical punch force responses, described by Eq. (6), for constant blank holder forces, F_{b1} and F_{b2}, respectively.

Integrating Eq. (2) from t_s^- to t_s^+ and allowing t_s^- to approach t_s^+ leads to

$$F_{pc2}(F_{b2},t_s)-F_{pc1}(F_{b1},t_s)=\left.\frac{\partial F_p}{\partial F_b}\right|_{\substack{F_b=F_{b2}\\ t=t_s}}\cdot(F_{b2}-F_{b1}) \tag{8}$$

Note that the integral of $\partial F_p/\partial t$ approaches zero as t_s^- approaches t_s^+ because Eq. (4) shows that $\partial F_p/\partial t$ is finite. In addition, $\dot{F}_b=(F_{b2}-F_{b1})\delta(t-t_s)$ because F_b is defined as shown in Fig. 4.

If the assumption that F_{b2} approaches F_{b1} is made, the following result can be obtained from Eq. (8),

$$\frac{\partial F_p}{\partial F_b}\simeq\frac{\partial F_{pc}}{\partial F_b} \tag{9}$$

Substituting Eqs. (4) and (9) into Eq. (2) leads to the following process model,

$$\dot{F}_p=-\frac{1}{\tau(F_b)}F_p+\frac{\alpha(F_b)}{\tau(F_b)}F_b+\frac{\partial F_{pc}}{\partial F_b}\dot{F}_b \tag{10}$$

Model parameters (i.e., $\alpha(F_b)$ and $\tau(F_b)$) can be obtained from constant blank holder force experiments.

Note that the proposed process model, Eq. (10), is based on two assumptions:

Assumption I: The punch force trajectory for constant blank holder force can be mathematically described by Eq. (6).

Assumption II: The punch force trajectory for step-change blank holder force can be mathematically described by Eq. (7).

These two assumptions are independent of any forming process. Therefore, the process model for sheet metal forming described by Eq. (10) applies to any sheet metal forming process as long as the process satisfies these two assumptions.

2.2 Model Uncertainty. Different blank size, sheet thickness, material properties and tooling shapes will generate different punch force trajectories for the same applied blank holder force trajectory [1]. Since model parameters (i.e., $\alpha(F_b)$ and $\tau(F_b)$) are obtained using experimental data for constant blank holder force and Eq. (6), different model parameters will be obtained from different blank size, sheet thickness, material properties and tooling shapes. For example, different material yield point, thickness, anisotropy and surface characteristics could all influence the punch force trajectory for the same blank holder force trajectory, and in turn, influence $\alpha(F_b)$ and $\tau(F_b)$. Therefore, $\alpha(F_b)$ and $\tau(F_b)$ depend on blank size, sheet thickness, material properties and tooling shapes.

In a forming operation, blank size, sheet thickness, material properties and tooling shape are assumed to be constant but in fact vary from run to run. Sheet thickness may vary within a sheet, and between different sheets, though the variation could be small. Material properties may also vary in the same way and tooling wear may be small but unknown. All of these variations will cause system characteristics to change slightly, but unpredictably. The model uncertainty can then be specified in terms of variations in $\alpha(F_b)$ and $\tau(F_b)$.

Experimental results [14] showed that lubrication affects the punch force. Since lubrication is assumed to be a disturbance to the system, it will have substantial influence on F_p through its effect on F_b.

The model uncertainty specified in terms of small variations in $\alpha(F_b)$ and $\tau(F_b)$ describes the influence of small variations in blank size, sheet thickness, material properties and tooling shape due to die wear on the characteristic relationship between F_b and F_p. The model uncertainty, however, does not describe the influence of different material and tooling on the characteristic relationship. Different material and tooling will lead to different $\alpha(F_b)$ and $\tau(F_b)$, which is not described by the model uncertainty.

2.3 Disturbances. The disturbance in Fig. 3 is due mainly to variation in the friction force or the lubrication. Some friction data were used to develop a friction model (see Appendix A) which is used later to derive a disturbance model.

Experiments on *u*-channel forming showed that the sheet metal under the punch is almost motionless if the alignment of tooling is proper. Therefore, the friction force under the punch is assumed to have no influence on forming. The friction force at the punch corner can also be assumed to have no influence on the characteristic relationship between F_b and F_p, as will be shown later. The friction force on the blank holder shoulder is ignored because it will have an additive effect on the disturbance. (See Appendix B.) Consequently, the disturbance is assumed to arise from the friction force between the sheet metal and the blank holder with or without fixed height drawbeads.

It is further assumed that the stamping process is a quasi-static pseudo-steady process. Because of static equilibrium, the forces in Fig. 1 are related by

$$F_p = 2F_r \sin\beta \tag{11}$$

Since Eq. (11) holds regardless of the influence of the friction force at the punch corner, the friction force at the punch corner has no effect on the characteristic relationship between F_b and F_p. Since the friction force on the blank holder shoulder is ignored, F_r is equal to the friction force between the sheet metal and the blank holder.

From a physical point of view, the blank holder force and the friction coefficient affect the blank restraining force or the friction force. Since only the blank holder with or without fixed height drawbeads is used as the mechanism to control material flow, Coulomb friction can be assumed and can be described by the following equation

$$F_r = \mu \cdot F_b \tag{12}$$

where μ is the friction coefficient.

If the influence of friction is to be modeled as a disturbance, it must be specified in terms of the blank holder force. From Eq. (11), similar blank holder restraining force trajectories will produce similar punch force trajectories as long as the experimental conditions are the same. From Eq. (12), similar blank holder force trajectories cannot ensure similar blank holder restraining force trajectories because of μ. Therefore, it is possible to specify the influence of μ on F_r in terms of F_b.

The friction coefficient is the sum of a nominal value, μ_0, and a variation part, $\Delta\mu$. (See Appendix A.) From Eq. (12), a variation in μ, or $\Delta\mu$, causes a variation in F_r, i.e. ΔF_r:

$$\Delta F_r = \Delta\mu \cdot F_b \tag{13}$$

Since the disturbance force F_d in Fig. 3 is assumed to represent the influence of $\Delta\mu$ on F_r, i.e. ΔF_r, then

$$\Delta F_r = \mu_0 \cdot F_d \tag{14}$$

From Eqs. (13) and (14), the disturbance force F_d can be represented by:

$$F_d = \frac{\Delta\mu}{\mu_0} \cdot F_b \tag{15}$$

For a lubricant, μ_0 is assumed to be reasonably constant and $\Delta\mu$ is assumed to be constant but unknown. (See Appendix A.) If the blank holder force is constant, then Eq. (15) leads to representation of F_d as an unknown constant. Therefore, the unknown disturbance force F_d can be modeled as a step function.

Equation (15) can also describe the influence of different lubrication on the characteristic relationship between F_b and F_p for the same material and tooling. Assuming that the variation part of the friction coefficient is much smaller than the nominal value,

$$F_{r1} = \mu_{01} \cdot F_b \tag{16}$$

$$F_{r2} = \mu_{02} \cdot F_b \tag{17}$$

where μ_{01} is the original nominal friction coefficient and μ_{02} is the other one. The difference between F_{r1} and F_{r2} becomes

$$\Delta F_r = F_{r2} - F_{r1} = (\mu_{02} - \mu_{01}) \cdot F_b \tag{18}$$

which can be represented by the disturbance, F_d, in the blank holder force, and assuming the original nominal friction coefficient is valid,

$$\Delta F_r = \mu_{01} \cdot F_d \tag{19}$$

Therefore, the disturbance caused by different lubrication can be represented by Eq. (15) where $\Delta\mu = \mu_{02} - \mu_{01}$ and μ_0 becomes μ_{01}.

3 Experiments

3.1 Experimental Setup. Figure 5 shows a schematic of the forming simulator used to conduct the experiments. The forming simulator is a double action hydraulic press. Its digital control system uses two PID controllers to make the punch displacement and the blank holder force track some predefined trajectories individually. The predefined trajectories and the controller gains can be adjusted through the computer. Figure 6 shows the tooling for the *u*-channel forming. Material flow is controlled by a set of blank holders with fixed height draw-beads. The tooling dimensions are shown in Table 1. The experimental conditions are given in Table 2. The servo loop update rate shows how quickly the servo control loop can be updated while the data sampling interval

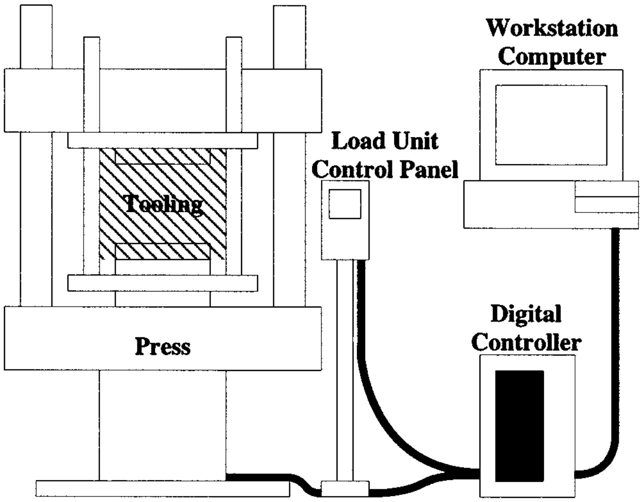

Fig. 5 Forming simulator

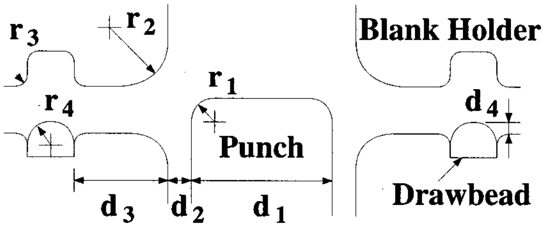

Fig. 6 Tooling for *u*-channel forming

Table 1 Tooling dimensions (mm)

r_1	r_2	r_3	r_4	d_1	d_2	d_3	d_4
2.50	6.35	6.35	6.35	50.0	8.0	20.0	4.0

Table 2 Experimental conditions for the *u*-channel forming

Punch velocity, v_p	5 mm/sec
Final punch displacement, x_{pf}	50 mm
Servo loop update rate	3790 Hz
Data sampling interval, T_s	0.01 sec
Lubrication	Dry
Material	Al 6022-T4
Blank size	260 × 100 × 0.922 mm

shows how quickly the data can be acquired. Samples and tooling are cleaned by acetone to maintain the same lubrication condition during tests.

3.2 Blank Holder Force Trajectories. Figure 7 shows typical blank holder force trajectories used in the experiments. Time 0 is the instant when the punch touches the blank, and t_s is the instant when a step change occurs. The time when a test is finished is t_f and at $t=t_f$ the punch displacement, x_p, reaches the final displacement, x_{pf}. The beginning and end levels of blank holder force for a variable blank holder force trajectory are F_{b1} and F_{b2} respectively, and F_{b3} denotes the constant level for a constant blank holder force trajectory. Trajectory (1) is a constant blank holder force, trajectory (2) is a blank holder force with a step change, trajectory (3) is a ramp blank holder force, and trajectory (4) is a half sine blank holder force. Table 3 lists the actual experimental trajectories used in this investigation.

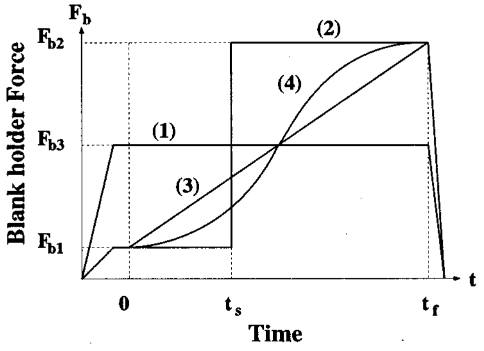

Fig. 7 Experimental blank holder force trajectories

Table 3 Parameters of blank holder force trajectories in experiments

F_b shape	F_{b1} kN	F_{b2} kN	F_{b3} kN	t_s sec
Constant			10	
			20	
			30	
			40	
			50	
			60	
			70	
Step Change	10	70		2
	10	70		6
	10	70		8
	10	70		9
Ramp	10	70		
	70	10		
Half Sine	10	70		
	70	10		

4 Results

Figure 8 shows experimental punch force trajectories for constant blank holder force. Three tests were performed for each constant blank holder force. As shown in the figure, the punch force generally increases as the blank holder force increases. Higher blank holder force also produces higher variation in punch force. However, Eq. (6) is a good approximation for the punch force-punch penetration trajectories.

Fitting the experimental data for constant blank holder force to Eq. (6) leads to α and τ, as shown by the ‘‘Curve-fitted data’’ in Fig. 9. The ‘‘Curve-fitted data’’ for α and τ vary slightly for each value of the blank holder force. Also α and τ vary with the magnitude of the blank holder force. The variation in α falls within the range of (0.6–1.3) and in τ within the range of (2.0–3.6).

Approximate polynomials for $\alpha(F_b)$ and $\tau(F_b)$ (i.e., the solid lines in Fig. 9) are given by

$$\alpha(F_b)=1.5235-2.7474\times10^{-2}\cdot F_b+2.2717\times10^{-4}\cdot F_b^2 \tag{20}$$

$$\tau(F_b)=1.5682+1.0794\times10^{-1}\cdot F_b-3.7275\times10^{-3}\cdot F_b^2 +3.6558\times10^{-5}\cdot F_b^3 \tag{21}$$

These polynomials are used in the process model (Eq. (10)) to simulate and predict punch force trajectories for variable blank holder forces.

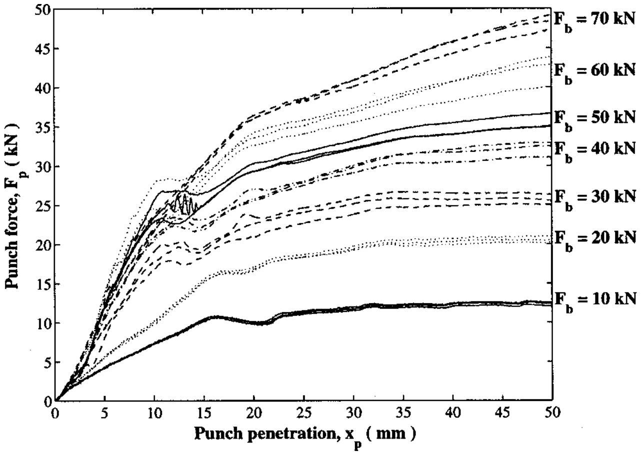

Fig. 8 Experimental punch force trajectories for constant blank holder force

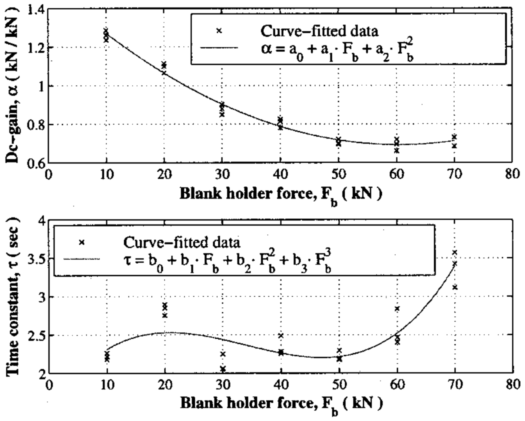

Fig. 9 Resultant model parameters, α and τ

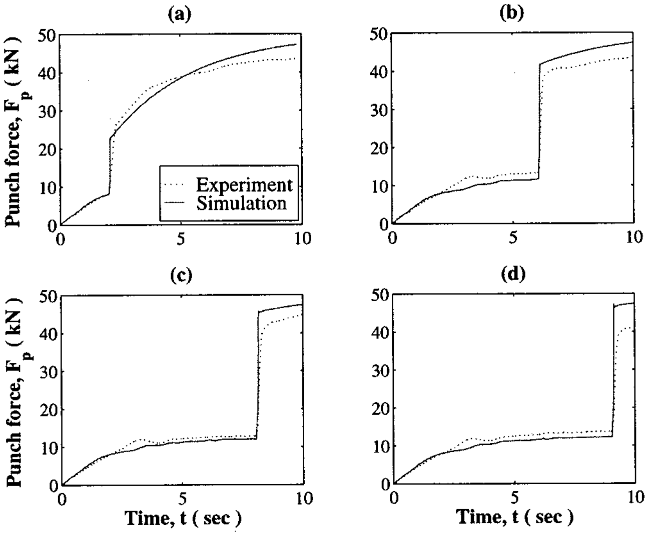

Fig. 10 Experimental and predicted punch force trajectories for variable blank holder force with a step change

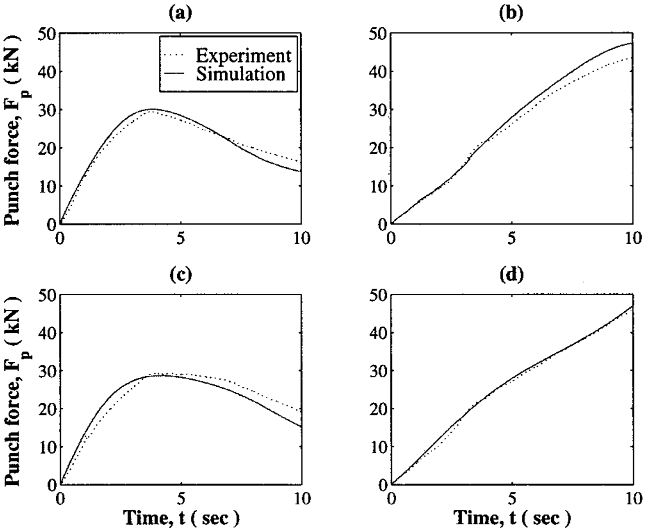

Fig. 11 Experimental and predicted punch force trajectories for continuously variable blank holder force

Figure 10 shows experimental and predicted punch force trajectories for variable blank holder force with a step change. The predicted punch force trajectories are calculated using Eq. (10). Figures 10(*a*), 10(*b*), 10(*c*), and 10(*d*) are for blank holder force with a step change at 2, 6, 8 and 9 sec (i.e., 10, 30, 40, and 45 mm of x_p at a constant velocity of $v_p = 5$ mm/sec) respectively. Figure 11 shows experimental and predicted punch force trajectories for continuously variable blank holder force, ramp or half sine. Figure 11(*a*) is for the half sine down blank holder force, Fig. 11(*b*) is for the half sine up blank holder force, Fig. 11(*c*) is for the ramp down blank holder force, and Fig. 11(*d*) is for the ramp up blank holder force. Figures 10 and 11 show a good correlation between experimental and predicted punch force trajectories.

5 Discussion

The two assumptions used to develop the process model (Eq. (10)) came from examining Adamson's results for *u*-channel forming with flat blank holder [1], namely:

1. Punch force trajectories for constant blank holder force behave like the response of a first order model to a step input.
2. An abrupt change in F_b produces an abrupt change in F_p.

In fact, these assumptions are independent of sheet metal forming processes. Therefore, the derived process model is a general model for any forming process which satisfies such assumptions.

A good correlation between simulation using the proposed process model and experiments was obtained using a flat blank holder [24]. The same good correlation was also obtained in this work using a flat blank holder with fixed height drawbeads (Figs. 10 and 11). Therefore, the proposed process model is applicable whether the flat blank holder or the fixed height drawbeads are used.

Adamson [1] performed constant and step-change blank holder force (i.e., trajectories (1) and (2) in Fig. 7) experiments. Since the process controller changes the blank holder force in real time, the process model (Eq. (10)) is evaluated using continuously varying blank holder force (i.e., trajectories (3) and (4) in Fig. 7). Figure 11 shows that the process model can be used for continuously varying blank holder force trajectories. This means that this process model can be used with confidence as the basis for computer simulations and controller design.

A piecewise linearized model may be a special case of the developed process model (Eq. (10)) if the blank holder force trajectory has the shape of a staircase. A model developed by Majlessi et al. [23] had two components: a fifth order model for the first half of punch travel and a seventh order model for the second half of punch travel. This model is in fact a piecewise linearized model. Hence, it could be a special case of the new process model (Eq. (10)). The new process model (Eq. (10)) is a first order nonlinear model that considers the effect of F_b on the model dynamics (i.e., model parameters are functions of F_b) and the effect of jumps in the blank holder force (i.e., $\partial F_{pc}/\partial F_b \dot{F}_b$ in Eq. (10)).

The process model (Eq. (10)) is easy to implement because the two unknowns, $\alpha(F_b)$ and $\tau(F_b)$, can be obtained from constant blank holder force experiments. This model can predict the punch force trajectory for a given blank holder force trajectory but it cannot predict tearing, wrinkling, or dimensional accuracy.

The values of model parameters, $\alpha(F_b)$ and $\tau(F_b)$, shown in this paper differ from those presented in a previous publication [24]. In this work, Al 6022-T4 is used whereas Al 6111-T4 was used in the previous publication. Blank size and tooling dimensions are also different. Fixed height drawbeads are used in this study while a flat binder was used in the previous work.

Model uncertainty can be developed from variations in $\alpha(F_b)$ and $\tau(F_b)$. Figure 9 gives the ranges of $\alpha(F_b)$ and $\tau(F_b)$, (0.6–1.3) and (2.0–3.6), and these ranges can be used to determine model uncertainty.

The disturbance model is an unknown constant which applies only for a constant blank holder force. For a staircase shape trajectory, the blank holder force is constant during each step and the previous model can be applied for each step. F_d is, therefore, constant but indeterminate for each step. As a result, F_d can be modeled as a random sequence for a staircase blank holder force. This means that a random sequence can be used as the disturbance in the closed-loop simulation since F_b, for a digital controller, is a staircase sequence.

The success of a proportional-plus-integral process controller in eliminating the influence of lubrication [13] can be explained as follows. A step function as the disturbance can capture the influence of different lubrication on the characteristic relationship between F_b and F_p. In addition, a proportional-plus-integral controller can intrinsically compensate for a step disturbance.

The sheet metal forming model, consisting of the process model (Eq. (10)) and characteristics of the model uncertainty and the disturbance, can lay the foundation for process controller design. Stability of the closed-loop system must be insensitive to variations in model parameters. The selection of the process controller configuration must depend on the dynamics of the disturbance. For example, a process controller with an integral action can compensate for the influence of a step disturbance. The performance of different controllers can be evaluated through simulation using the process model. The derived process model is nonlinear, and this suggests the need for nonlinear controller design for stamping process control.

6 Conclusions

The model for control of sheet metal forming, as shown in Fig. 3, specifies parameters in the forming process (e.g., blank size, sheet thickness, material properties, tooling shape, and lubrication) in terms of control terminology (e.g., process model, model uncertainty, and disturbance). The developed process model (Eq. (10)), with the blank holder force as its input and the punch force as its output, has the following features:

1 It is a first-order nonlinear model that can be easily determined from constant blank holder force experiments.

2 It captures the effects of blank size, sheet thickness, material properties and tooling shape in sheet metal forming through the parameters, α and τ, which are experimentally determined and depend on blank size, sheet thickness, material properties and tooling shape.

3 It captures the effects of the blank holder force on the process dynamics because α and τ are functions of F_b.

Model uncertainty due to small variations in blank size, sheet thickness, material properties and tooling shape due to die wear can be represented by small variations of the model parameters (i.e., α and τ) of the process model. For the open-loop system with a constant input, the characteristic behavior of the friction, due to change in $\Delta\mu$ for identical lubricant or change in μ_0 for different lubricant, can be modeled as a step disturbance input. The present approach offers all necessary information for process controller design.

The process model (Eq. (10)) was originally developed based on experiments without drawbeads, but this work shows that it can also capture the characteristic behavior of fixed height drawbeads. In addition, it can also adequately describe the response of continuously varying blank holder force trajectories and, therefore, it can be used with confidence for controller design.

Acknowledgments

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Appendixes

A Friction Model for Sheet Metal Forming. Wang et al. [25] showed the effect of lubrication on the friction coefficient at the die corner (Fig. 12). Different lubricants produced different friction coefficients [26]. The coefficient of friction was not constant but varied with the punch stroke [27]. Therefore, a nominal value (μ_0) is assumed to describe the typical friction behavior of a lubricant. Change in lubricant produces change in μ_0 and μ_0 may be a function of the punch stroke.

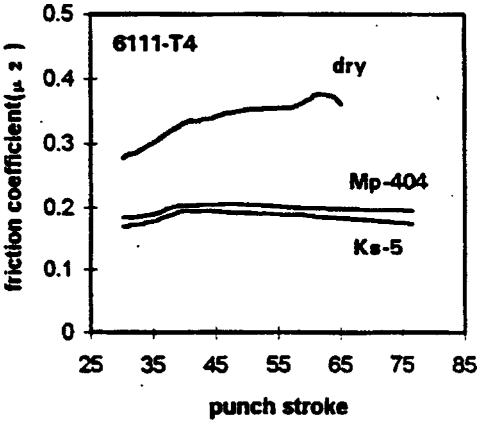

Fig. 12 Effect of lubrication [25]

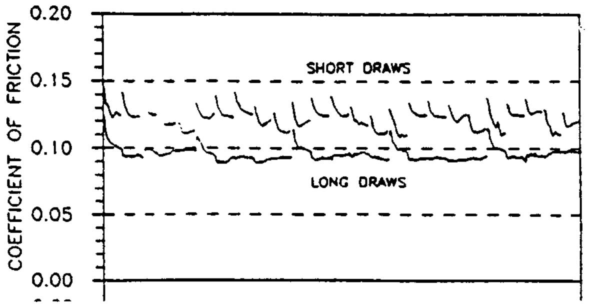

Fig. 13 Development of friction in drawing bare steel with neat mineral oil [28]. The abscissa represents draw length.

Schey and Watts [28] showed the development of friction in drawing bare steel with neat mineral oil (Fig. 13). Results showed that there was an offset between any two draws. The offset seemed to be constant during a test but to vary between tests. Hence, an unknown constant ($\Delta\mu$) is assumed to describe the offset.

According to the above observations, the coefficient of friction (μ) can be represented by the sum of the nominal value (μ_0) and the unknown constant ($\Delta\mu$):

$$\mu=\mu_0+\Delta\mu \tag{22}$$

For a given lubricant, μ_0 describes the typical friction behavior during a test and $\Delta\mu$ is related to the variation in friction behavior between tests under the same conditions. For a given lubricant, μ_0 is reasonably constant (see Fig. 12) and $\Delta\mu$ is reasonably constant but unknown (see Fig. 13).

B Disturbance Due to the Friction Force on the Blank Holder Shoulder. The friction effect on the blank holder shoulder influences the characteristic relationship between F_p and F_b, because the friction coefficient can be calculated as

$$\mu_b=\frac{1}{\beta}\ln\frac{F_r}{F_f} \tag{23}$$

where μ_b is the friction coefficient on the blank holder shoulder, F_f is the blank restraining force or the friction force within the sheet metal between the blank holders, F_r is the blank restraining force inside the gap between the punch and the blank holder, and β is the contact angle [25]. If the friction effect on the blank holder shoulder is ignored, F_f equals F_r.

Assuming that variation in μ_b will cause variation in F_f leads to

$$\mu_b+\Delta\mu_b=\frac{1}{\beta}\ln\frac{F_r}{F_f+\Delta F_f} \tag{24}$$

Also, assuming small variations leads to

$$\Delta\mu_b=-\frac{1}{\beta}\cdot\frac{\Delta F_f}{F_f} \tag{25}$$

The Coulomb friction between the sheet metal and the blank holder,

$$F_f=\mu\cdot F_b \tag{26}$$

ΔF_f is represented by the disturbance, F_{d1}, which is variation in F_b:

$$\Delta F_f=\mu\cdot F_{d1} \tag{27}$$

Substituting Eqs. (26) and (27) into Eq. (25) leads to

$$F_{d1}=(-\beta\Delta\mu_b)\cdot F_b \tag{28}$$

Therefore, the friction effect on the blank holder shoulder can be modeled as a disturbance. The effect is additive because if the friction effect on the blank holder shoulder is considered, F_{d1} can be added to F_d. For constant F_b and $\Delta\mu_b$, F_{d1} can be modeled as a ramp function because β increases as the punch penetration increases.

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