Chapter 5
Laboratory Development of Process Control

Abstract In sheet metal forming processes the blank holder force controls the material flow into the die cavity, which is critical to producing a good part. Process control can be used to adjust the blank holder force in-process based on tracking a reference punch force trajectory to improve part quality and consistency. Key issues in process control include process modeling as well as process controller and reference punch force trajectory design. In this chapter a systematic approach to the design and implementation of a suitable process controller and an optimal reference punch force trajectory is presented. The approach includes the modeling for controller design of the sheet metal forming process, design of the process controller, and determination of the optimal punch force trajectory. Experimental results from U-channel forming on a laboratory forming simulator show that a suitable process controller can be designed through simulation and an optimal reference punch force trajectory can be synthesized through experiments. The proposed development will be useful in designing and implementing process control in sheet metal forming processes as described in subsequent chapters.

5.1 Background on Process Control for Stamping

The control of material flow into the die cavity is crucial for good part quality and consistency, and the blank holder is used to control the material flow. Previous research has shown that varying the blank holder force during forming can improve part quality (Adamson et al. 1996; Ahmetoglu et al. 1995; Schmoekel and Beth 1993) and consistency (Adamson et al. 1996; Hsu et al. 1999). It is worth pointing out that mechanical presses are being retrofitted with hydraulic multi-point cushion systems to provide more control of the forming process (Siegert et al. 1998; Lim et al. 2010, 2012) and many new stamping presses are hydraulic in design. Such press technologies will facilitate the implementation of the process control ideas presented in this book.

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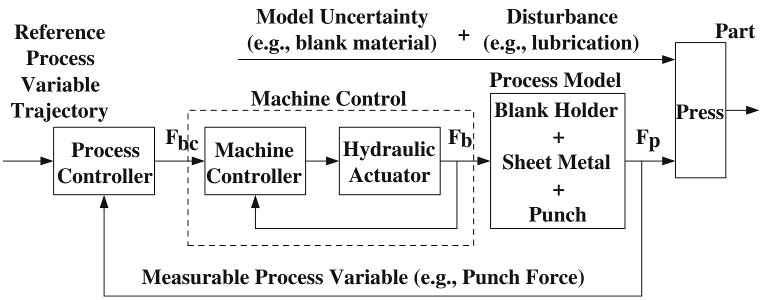


Fig. 5.1 Process control of sheet metal forming

As discussed previously, a strategy for controlling sheet metal forming through the application of variable blank holder force is process control (see Fig. 5.1). In this strategy a measurable process variable (e.g., punch force) is controlled by following a predetermined (e.g., punch force vs. punch stroke or vs. time) reference trajectory through manipulation of the blank holder force (Adamson et al. 1996; Hsu et al. 2002). This strategy was able to produce cups with "optimal" height regardless of initial blank holder force and friction conditions (Hardt and Fenn 1993). Other measurable process variables (e.g., draw-in and friction force) have also been reported (Siegert et al. 1995, 1997; Sim and Boyce 1992).

To systematically design a suitable process controller, the process model in Fig. 5.1 must be identified first. Most sheet metal forming models are based on finite element analysis, which are very complex and, therefore, are not suitable for controller design (Majlesi et al. 1992). A piecewise linear model for controller design has been developed in (Majlesi et al. 1992). However, this model cannot be used in closed-loop simulation, because it cannot capture the characteristic nonlinear behavior of a sheet metal forming process. Issues in modeling for control of sheet metal forming have been more fully addressed in (Hsu et al. 2000a, b), especially, from a control point of view. Methods of system identification have been well developed (Ljung 1999) and can be applied to stamping process modeling once a suitable model structure is established (Lim et al. 2010).

The most popular structure for the process controller itself is a proportional-plus-integral controller (Hardt and Fenn 1993; Siegert et al. 1995; Sim and Boyce 1992). However, controller parameters are typically determined by trial and error (Morari and Zafiriou 1989). Although design of process controllers has been well developed (Hsu et al. 1999, 2002; Lim et al. 2010, 2012), its application to sheet metal forming is still being investigated. The reference trajectory in process control is also important to ensure good part quality in sheet metal forming (Hsu et al. 2000b). The reference trajectory has typically been determined experimentally or numerically (Hardt and Fenn 1993; Sim and Boyce 1992), often based upon operator experience. However, optimization of the reference trajectory has not been well addressed (Hsu et al. 2000b, 2002).

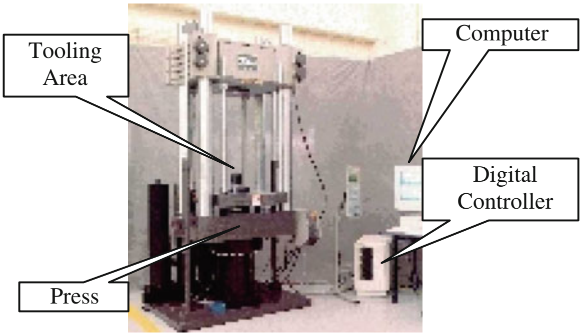


Fig. 5.2 Experimental forming simulator

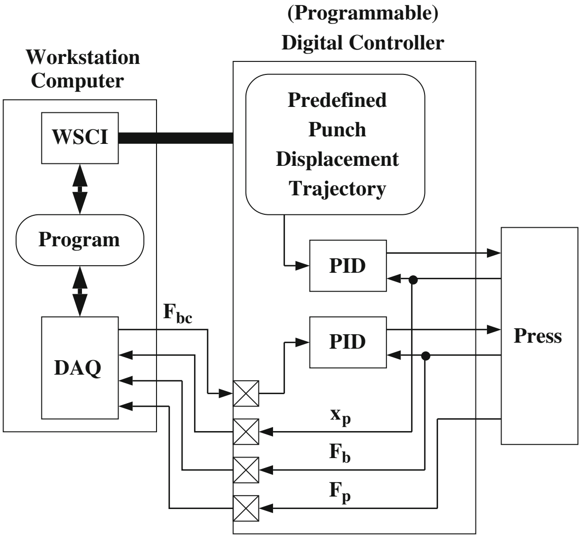
Key issues regarding the application of process control to sheet metal forming include process modeling for controller design, design of an appropriate process controller and design of an optimal reference trajectory. The purpose of this chapter is to address these key issues to systematically design and implement process control in sheet metal forming based on laboratory experiments using a forming simulator (Hsu et al. 2002).

5.2 Experimental Facility and Model Development

Process control experiments were conducted on a double action laboratory hydraulic forming simulator equipped with a proportional-integral-derivative (PID) digital controller as shown in Fig. 5.2. The press load capacity is 680 kN for the punch and 700 kN for the binder. The digital controller allows the blank holder force, F_b, to track a predetermined reference trajectory, F_{bc}. Thus, this digital PID controller is the realization of the "Machine Controller" block in Fig. 5.1. Implementation of process control on this forming simulator is achieved in the workstation computer as shown in Fig. 5.3 (Hsu et al. 1999, 2000a, 2002). The component labeled "DAQ" is a data acquisition board. It acquires data (i.e., punch force F_p) from the digital controller (realization of the outer feedback path in Fig. 5.1) and feeds the calculated blank holder force command, F_{bc}, to the digital PID machine controller. The "Program" block together with the "DAQ" block in Fig. 5.3 is the realization of the "Process Controller" block in Fig. 5.1. The "WSCI" block is the original workstation communication interface.

A comparison of machine and process control for U-channel forming has demonstrated the superiority of process control over machine control only (Hsu et al. 1999, 2002). Figure 5.4 shows relative tracking errors for machine and process control under dry and lubricated conditions. The results show that process control can maintain the same punch force trajectories under different lubrication conditions while machine control cannot. Table 5.1 shows average measured channel heights for the cases shown in Fig. 5.4. The measurements show that

Fig. 5.3 Experimental implementation of the process controller



process control improves consistency in channel height, despite change in lubrication. Therefore, consistency in channel height can be related to consistency in punch force trajectories.

5.3 Establishing the Reference Punch Force

The importance of the reference punch force can be shown by comparing measured channel heights for different reference punch force trajectories (Hsu et al. 2000b, 2002). Figure 5.5 shows two experimental reference punch force trajectories. Table 5.2 shows measured channel heights for these two trajectories. Trajectory (b) produces better parts because springback is minimized and the measured channel heights are closer to the desired channel height (50 mm).

5.4 Process Controller Design

Based on the above experimental results, two important considerations emerge:

- Evaluation of the tracking performance of the process controller.
- Selection of the reference punch force trajectory.

These two considerations will be addressed here. Modeling a sheet metal forming process involving hydraulically controlled single cylinder binder for

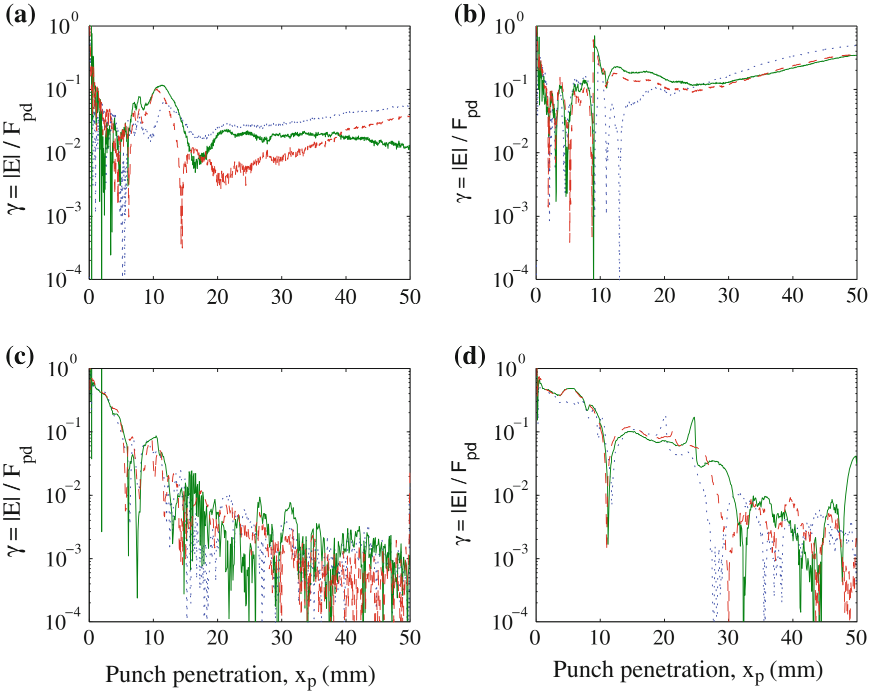


Fig. 5.4 Relative tracking errors. **a** Machine control/dry. **b** Machine control/MP−404. **c** Process control/dry. **d** Process control/MP−404

Table 5.1 Average measured channel heights (mm) for machine and process control under different lubrication conditions

Control type\lubrication	Dry	MP-404
Machine	47.600	46.211
Process	47.557	47.659

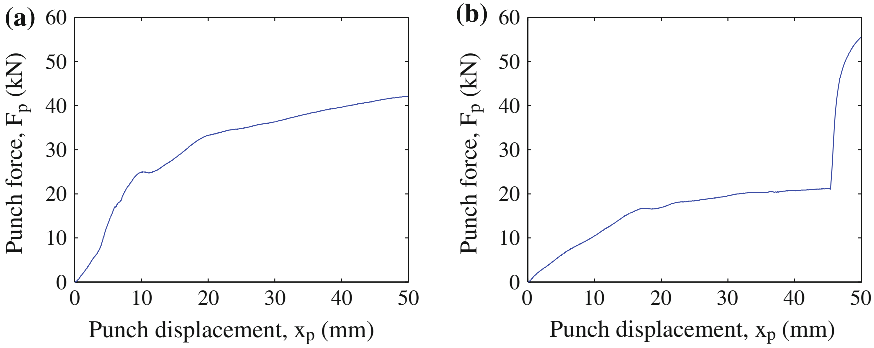
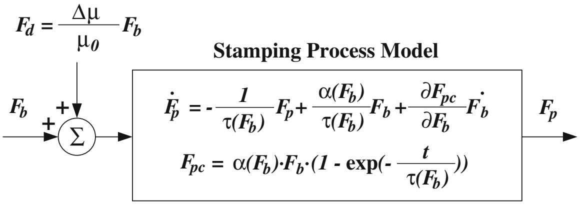


Fig. 5.5 Experimental reference punch force trajectories

Table 5.2 Measured channel heights (mm) for reference punch force trajectories in Fig. 5.5

Trajectory	(a)	(b)
Test #1	47.447	49.251
Test #2	47.396	49.327
Test #3	47.828	49.276
Mean	47.557	49.285

Fig. 5.6 Process model of sheet metal forming



process controller design, which is a single-input single-output (SISO) system, has been investigated (Hsu et al. 2000a). The results of that study are shown in the block diagram in Fig. 5.6. The process model is a first-order nonlinear dynamic model. The disturbance, mainly due to variations in lubrication, is also shown. While this first order dynamic model is nonlinear, it can be linearized about a nominal constant value of the blank holder force, F_{b0} to obtain the response F_{pc}, which leads to a simple control design model as shown in the block diagram in Fig. 5.8. The gain, $\alpha(F_b)$, and time constant, $\tau(F_b)$, of this control-design model depend on the input, F_b. However, if changes in the blank holder force, F_b, are relatively small about the nominal value, F_{b0}, this simple model will be adequate. If not, then an adaptive process controller will be needed to handle the varying gain and time constant in the linearized model.

This model has been successfully used for the U-channel forming process for this laboratory forming simulator (Hsu et al. 2000a). Figure 5.7 shows a comparison of simulation and experimental results for different continuously variable blank holder force trajectories.

Because of the empirically derived process model, systematic study of process controller design can be conducted analytically and numerically before implementation (Hsu et al. 1999, 2002). For this SISO system, a proportional plus integral controller with feedforward action (PIF) has been investigated and successfully implemented in the forming simulator (Hsu et al. 1999, 2002). The block diagram of the controller is shown in Fig. 5.8. A first-order linear model with constant coefficients (i.e., gain and time constant) can be used to design the controller gains. The first-order linear model can then be replaced with the first-order nonlinear model in Fig. 5.6 to evaluate the tracking performance of the closed-loop system using the designed controller gains.

Figure 5.9 shows simulation results with the PIF process controller and the first-order nonlinear model. Figure 5.9a shows the blank holder force automatically generated by the PIF process controller. Figure 5.9b shows the reference punch

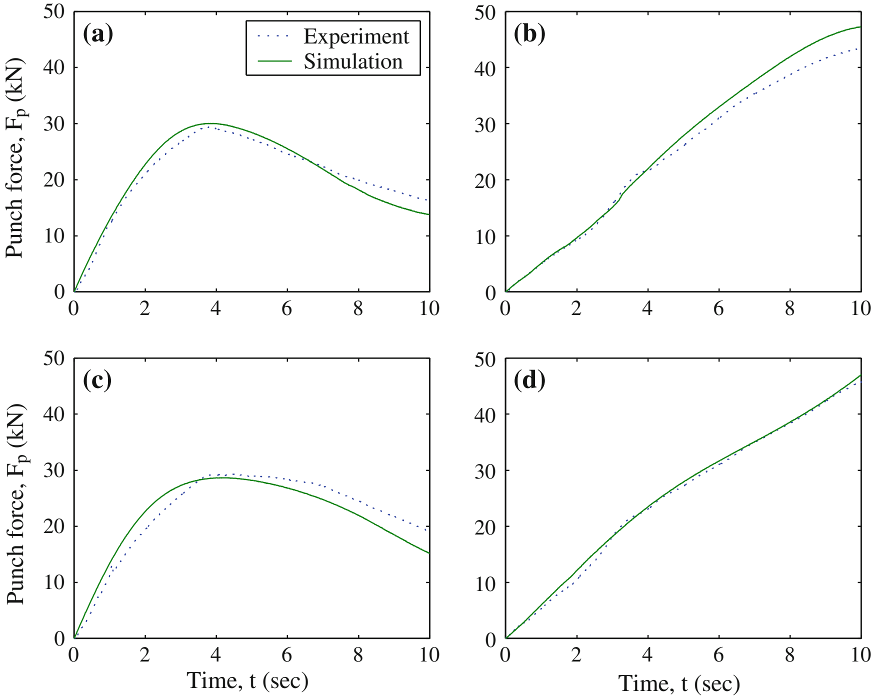
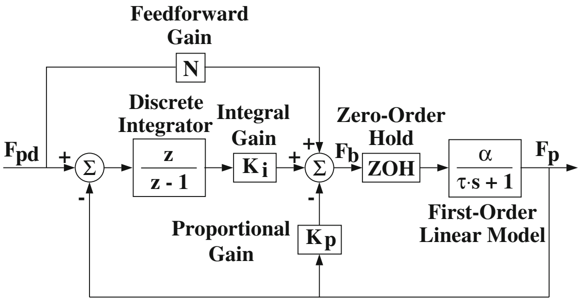


Fig. 5.7 Experimental and predicted punch force trajectories for different variable blankholder force trajectories

Fig. 5.8 Block diagram of the PIF control system



force trajectory, F_{pd}, and the punch force trajectory, F_p. Good tracking performance can be expected based on these simulation results.

Experimental results using the same PIF process controller and the same reference punch force trajectory are shown in Fig. 5.10. Although there was variation in the blank holder force trajectories, the punch force trajectories were similar. This indicates that the process controller works well despite unmodeled disturbances such as lubrication differences.

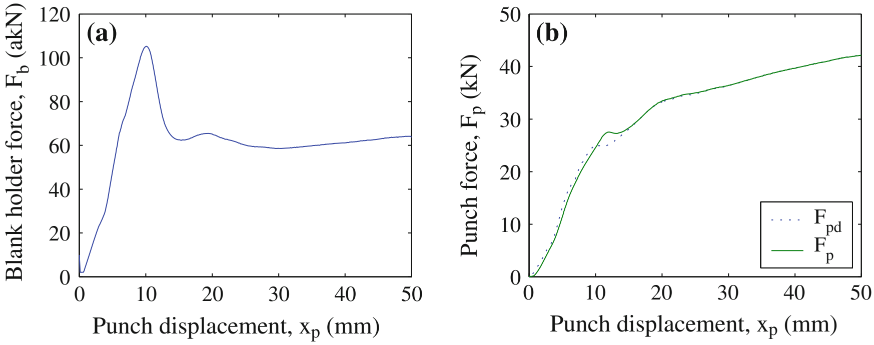


Fig. 5.9 Simulation results using the PIF process controller and the first-order nonlinear model

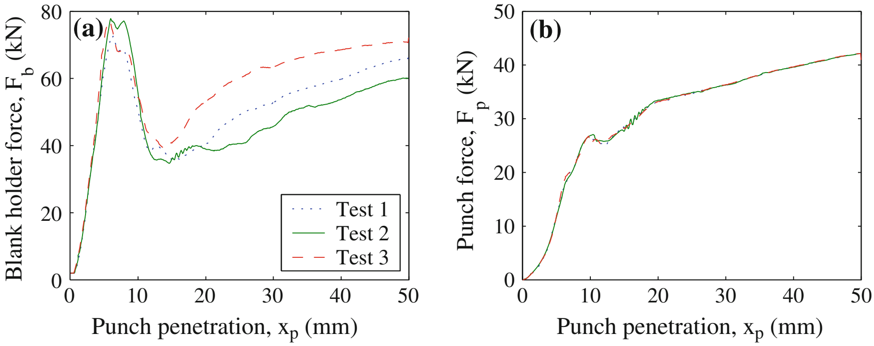


Fig. 5.10 Experimental results using the same PIF process controller and reference punch force trajectory

5.5 Punch Force Reference Trajectory Design

One method for obtaining an optimal reference punch force trajectory is to use design optimization methods (Hsu et al. 2000b; Montgomery 1997). With an ideal process controller, Fig. 5.1 can be simplified as shown in Fig. 5.11.

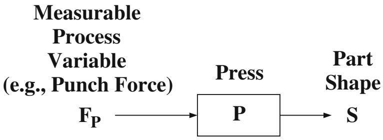
In this case, the stamped part shape, S, will be totally determined by the reference punch force trajectory, or equivalently, by the punch force trajectory, F_p. A mathematical expression can be used to describe the relationship in Fig. 5.11:

$$S = P\left(F_p\right) \tag{5.1}$$

The optimal punch force trajectoryF_p^* for a desired shape S_d can be obtained by solving Eq. (5.2):

$$F_p^* = \arg\min_{F_p \in D} E\left(P\left(F_p\right), S_d\right) \tag{5.2}$$

Fig. 5.11 Press with ideal process controller



where F_p^* is the optimal punch force trajectory, D is the safe domain for F_p without tearing and wrinkling, and E is the error cost function used to represent the difference between $P(F_p)$ and S_d.

To find F_p^* through optimization is still difficult. The challenges are:

1. To find the operator P which, given a punch force trajectory, yields the part shape.
2. To find the domain D which defines safe punch force trajectories.

Since current mathematical modeling of sheet metal forming uses finite element methods (Wang and Budinsky 1978; Wenner 1997), there is no simple expression for P or D. A procedure for solving Eq. (5.2) through parameterization and design of experiments can be used as follows:

1. Parameterize F_p and S. Parameters of F_p are the design variables and parameters of S are the response variables.
2. Identify an empirical relationship between the design and response variables.
3. Find the optimal design variables based on the empirical relationship. The optimal punch force trajectory corresponds to the optimal design variables.

Central composite design can be used for design of experiments to fit a second-order model (Montgomery 1997). Response surface methodology can also be used to find the optimal design variables. The methodology is summarized below, and a more detailed description can be found in (Hsu et al. 2000b, 2002).

Typically the smoother the optimal punch force trajectory is, the easier the process controller design is. Parameterization of F_p and S is realized by series expansion with orthogonal functions (e.g., Chebyshev polynomials). The desired smoothness of the optimal punch force trajectory can be ensured by the smoothness of the orthogonal functions.

The above procedure is a sequential one. The following results are from the application of the procedure to U-channel forming. The response variable is the channel height error, e_h, which is defined as the desired channel height minus the measured one. The punch force is parameterized through

$$F_p = a_1\varphi_1 - 2.04\varphi_3 + 5.03\varphi_5 - 1.69\varphi_7 \tag{5.3}$$

wherea_1 is the design variable and φ_i is the ith order Chebyshev polynomial. Coded design variables are usually used in design of experiments. The coded design variable, x_1, is

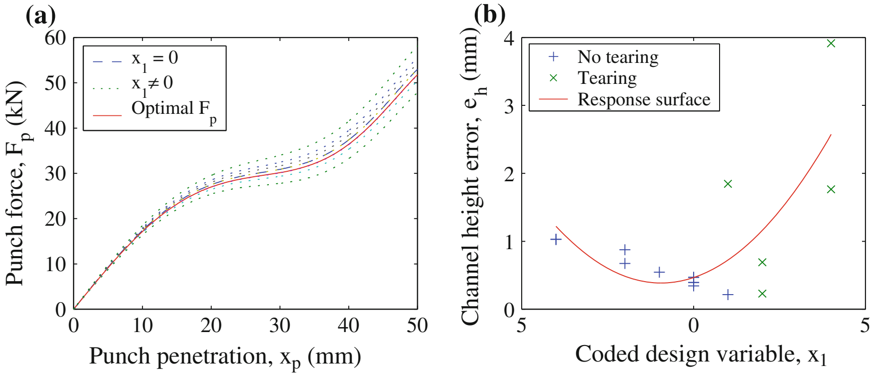


Fig. 5.12 **a** Designed punch force trajectories for the experiments and the optimal F_p. **b** Measured channel height errors and the fitted response surface

$$x_1 = \frac{a_1 - a_{10}}{\lambda a_{10}} \tag{5.4}$$

where a_{10} is the center of the design domain and λ is a scale factor. In this case, for example, a_{10} =51.69 and $\lambda = 0.025$.

Designed punch force trajectories corresponding to $x_1 = 4, 2, 1, 0, -1, -2$, and -4 for the experiments are shown in Fig. 5.12a. Channel height errors are shown in Fig. 5.12b. When tearing occurs, the channel height is assumed to be the height at failure. The optimal F_p in Fig. 5.12a corresponds to the minimum ($x_1^* = -0.94$) of the fitted response surface in Fig. 5.12b.

From a physical point of view, the true optimum in this case is a boundary optimum. Hence, the fitted response surface cannot predict the true optimum precisely. However, the fact that it is a statistically valid model and has a minimum indicates the existence of a true minimum nearby. Based on engineering judgment for the safety and robustness of the forming process, the optimal punch force trajectory is determined as the one corresponding to $x_1 = 0$.

While the laboratory tests described here to determine optimal punch force trajectories can be useful, in practice experienced press operators can quickly determine near-optimal punch force trajectories by trial and error during the die try out process. This is discussed further in subsequent chapters.

5.6 Concluding Remarks

Process control has been shown to improve part quality and consistency in the presence of process disturbances such as varying lubrication conditions. Key issues such as process controller and optimal punch force trajectory design have been addressed. A systematic approach to the application of process control to U-channel forming using a laboratory forming simulator has been presented. A process controller with good tracking performance and an optimal punch force trajectory have been developed.

While these results are important for demonstrating the key concepts of stamping process control, they also show that for practical implementation of these concepts in industrial stamping presses further work is needed. First, the SISO process controller demonstrated here on a laboratory forming simulator must be extended to multi-input multi-output (MIMO) process control for complex parts and industrial presses. Such an extension requires the design of a system with multiple measurements (e.g., punch force at multiple locations on the press) as well as the control of the blank holder force at multiple locations around the die. Second, convenient approaches to process modeling, and to determining the reference punch force trajectories, must be developed. Ideally, such approaches will require a very few (e.g., one) experiments to obtain the data needed for modeling, then automatically generate the required model. Third, adaptive process controllers will be needed to handle the varying parameters of the linearized controller design models for the process. Such adaptive controllers can improve performance, but must be carefully designed to avoid stability problems. Additional issues include the need for fast and accurate machine control (i.e., the inner loop in Fig. 5.1), methods for quickly and easily tuning the process controller gains, etc. The remaining chapters of the book address these and related issues and provide results from die try out and production tests.

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