7

Forming Processes: Monitoring and Control

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7.1 Introduction: Process and Control Objectives

Forming of metallic materials is the process of choice when complex net shapes with high levels of productivity are desired. Myriad processes, ranging from job-shop metal bending machines to very high speed stamping and forging presses are available. In all cases, the processes involve plastic deformation of the workpiece, and the resulting strong forces required to create plastic stresses. In this chapter, the problem of controlling such processes is considered from both the viewpoint of controlling the forming equipment and the deformation process itself. Several unique aspects of forming processes arise when considering control system design:

1. The process or plant transfer function becomes a static block with variable gain and severe hysteresis.
2. The plant (the forming process) is inherently variable owing to the sensitivity to the workpiece material properties.
3. An inherent lack of process degrees of freedom with respect to controlling overall part shape exists.

Metal forming can be divided into sheet-forming processes and bulk-forming processes (typically forging). The major difference is that the latter involves a complex three-dimensional flow of the material, while the former tends to be dominated by plane strain conditions, and the process is not intended to change material thickness, only the curvatures. In what follows, the sheet-forming processes are used as model processes, but much of what is developed applies to bulk-forming as well.

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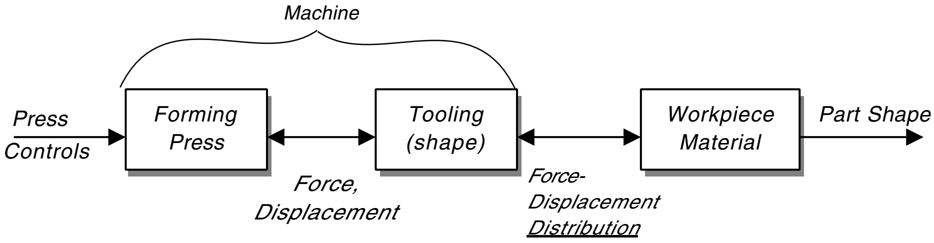

FIGURE 7.1 Basic block diagram for forming.

7.1.1 Process Control Issues

The objective of all sheet-forming processes is to alter the curvature of the material to achieve a target shape. In so doing, the material also may be intentionally stretched to aid in reducing shape errors and to induce strain hardening for strength properties. Accordingly, the control objective for the process is to achieve the desired shape, and (from a manufacturing point of view) to achieve this shape with rapid setup (flexibility) and minimal part-to-part variation (quality).

Application of control principles can have a great impact on all three: shape fidelity, variation reduction, and rapid changeover or setup. This control is accomplished either through the use of machine or process feedback to achieve higher accuracy and repeatability or by facilitating more mechanically complex machines to enhance process flexibility and control degrees of freedom. In all cases, the properties of control loops: tracking changing inputs (i.e., new part shapes), rejecting disturbances, and decreasing sensitivity to process parameter changes (e.g., tool–workpiece friction, constitutive property changes) are perfect matches to forming processes.

To help see this connection at a phenomenological level, it is useful to develop a set of block diagrams for these processes.

7.1.2 The Process: Material Diagram

A simple block diagram of the process is shown in Figure 7.1. Here the plant comprises:

- The forming machine or press, which provides the forming energy (force displacement)
- The tooling that takes this *lumped* energy and *distributes* it over the face of the tool–workpiece interface
- The workpiece material that plastically deforms according to the force or displacement field

In each block a set of constitutive properties determines how the energy or power variable pairs of each element relate to each other. For the machine blocks these properties would typically be the stiffness, mass, and damping of the machine as well as the overall geometry. For the workpiece, the set includes the large strain properties of the material and its initial geometry, which will affect how the distributed forces and displacements, and moments and curvatures are related. As will be seen, these material constitutive properties are the largest components of process variability in forming.

7.1.3 The Machine Control Diagram

In practice, the most common type of control used with forming processes is simple feedback of the machine outputs (herein referred to as *machine contro*l). As with any mechanical process, these outputs will be displacement or force, and control will involve application of servo-control technology to the actuators of the machine, whether eletrohydraulic or electromechanical. As shown schematically in Figure 7.2, closing this loop affords good regulation of these quantities, and will reject disturbances that enter the machine loop. These could include variations in the net force–displacement curve of the load (the workpiece) and variations in the machine properties such as friction and

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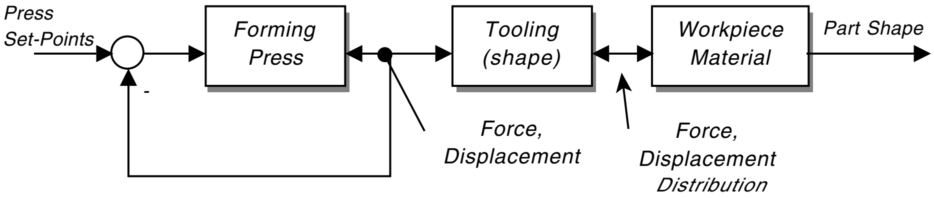

FIGURE 7.2 Closed-loop machine control for regulating force or displacement.

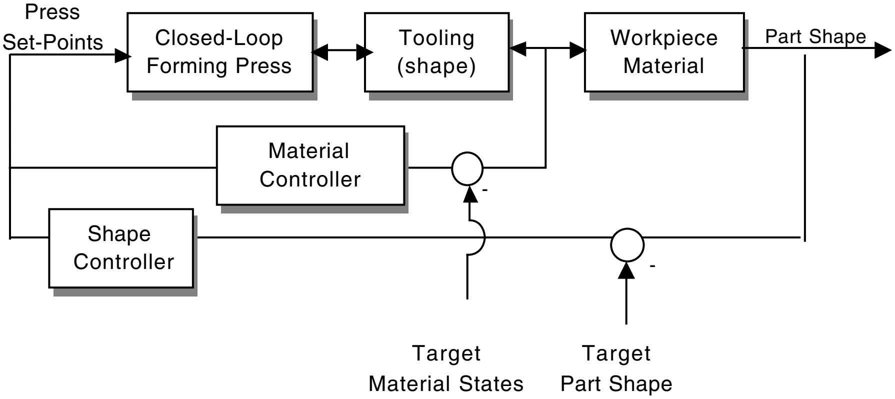

FIGURE 7.3 Material feedback and shape feedback control loops.

actuator nonlinearities and drift. It also can allow for a rapid change of set-points as production demands change. However, it cannot change the force–displacement distribution, and it leaves the part shape (which is the process output) outside the control loop.

Further stages of control can be attempted by actual measurement of forces and displacements at the tool (material control) and direct measurement of the resulting part shape (shape control). However, as shown in Figure 7.3, the only variables that can be manipulated are the press set-points, which are restricted to the limited number of actuator degrees of freedom. This, in turn, limits the process resolution, which is discussed below as the ultimate limit on process control effectiveness.

Many mechanical systems issues are involved in forming press control, but it is equally evident that even with precise control of force and displacement of the press, the resulting shape will still be a strong function of the tooling and the material itself.

To appreciate the latter aspect of forming processes it is necessary to consider the physics of forming as viewed in a control system's context.

7.2 The Plant or Load: Forming Physics

7.2.1 Mechanics of Deformation: Machine Load Dynamics

To consider the control of forming processes it is important to have at least a general understanding of the mechanics of the load as seen by a forming machine. Here a simple input–output description of forming is developed that can be shown to cover the basic phenomena of any forming process.

While a detailed model of the deformation process is well beyond the scope of this chapter, the basic phenomena of forming can be summarized by the classical unidirectional tensile stress–strain or force–displacement diagram. If we consider the simplest forming operation, that of stretching

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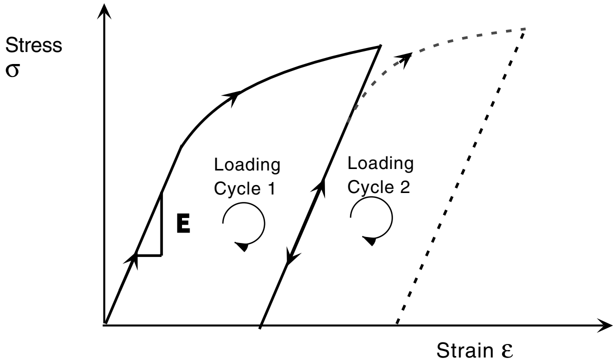

FIGURE 7.4 Cyclic loading stress–strain curve showing hysteresis and load-dependent offset.

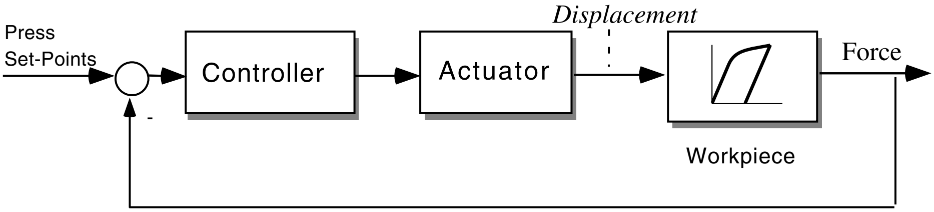

FIGURE 7.5 Simple tensile force control loop.

a bar of metal from an initial shape to a longer one, the force–displacement relationship of the workpiece is given by the constitutive stress–strain curve of the material. As shown in Figure 7.4 the curve includes not only the loading portion of the process, but also the unloading.

When looked at from a control system's perspective, the material appears to be a static block with nonlinear behavior. This arises from a power law-like plastic region, a hysteresis-like behavior arising from the elastic unloading behavior, and a history-dependent reference point owing to the permanent plastic deformation after loading beyond yield.

Because of the low mass of the material relative to the machine and tooling, the dynamics of the material block are usually ignored. However, the deformation process involves very low damping, and unless there is considerable sliding friction between the workpiece and tool, the contribution to overall system damping is minimal.

The variable slope in Figure 7.4 illustrates that if the sheet deformation process is within a control loop, the level of strain and its history can cause the gain of this element to vary widely, because the slope of the elastic region of the curve is typically more than an order of magnitude greater than the equivalent slope of the post-yield curve (the plastic modulus). Consider the impact of this on a closed-loop force controller for a simple tensile deformation. As shown in Figure 7.5, the actuator is providing a displacement output, and the tensile force generated in the material is measured and fed back to the controller. Figure 7.4 is the gain model for the workpiece block, and it indicates that the overall loop gain will be highly variable over the entire range of deformation, and will depend as well upon whether the displacement is increasing or decreasing.

7.2.2 Mechanics of Forming: Bending, Stretching, and Springback

Because all forming involves curvature change, some type of bending is always present. One of the most common and simplest forming processes is brakeforming, which is essentially three-point bending (see Figure 7.6). At any given cross-section along the arc length of the part, stress and strain distributions can be approximated by those of pure bending.

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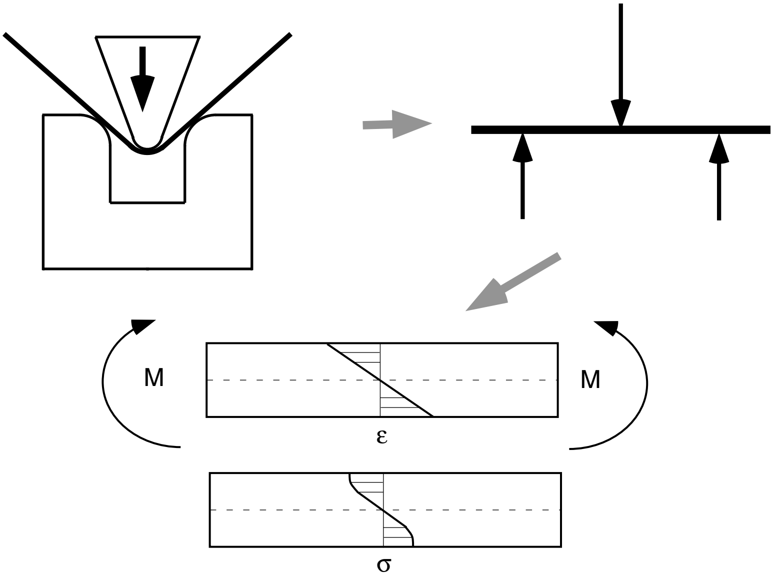

FIGURE 7.6 Simple brakeforming. Approximated as three-point bending with resulting stress and strain distributions.

With the resulting bi-directional stress distribution about the neutral axis, release of the forming loads leads to elastic unbending of the material. This curvature "springback" is the key source of error in forming processes, because it causes a difference between the curvature of the part when loaded to a known displacement and the final unloaded curvature.

To help reduce this springback and to achieve beneficial strain-hardening of the workpiece, the ends of the material are either constrained not to move or allowed to slip under a frictional force to provide an additive tensile force in the plane of the part. This process is shown in Figure 7.7 where it can be seen that the resulting stress distribution is now more uniform. As the tensile strain increases, the stress distribution becomes all positive and nearly constant. (For an idealized material that does not strain harden it will be constant.) As a result, the elastic unbending or springback of the part from the loaded curvature is greatly reduced. Consequently, for precision forming operations, or for operations where very small curvatures are involved (as with the stretch forming process used in aerospace) an intentional tensile force is added. Also, for three-dimensional forming problems, this tensile "bias" is also necessary to prevent in-plane buckling.

From the above it is obvious that for sheet forming, springback is the main source of errors, and variation in the springback will be the main source of process uncertainty. If we consider the simple bending example of Figure 7.6, the bending constitutive relationship can be written in terms of the moment–curvature relationship for the sheet. In the elastic region this is given by the simple relationship:

$$M = \frac{1}{EI} K \tag{7.1}$$

where
M = pure bending moment
K = resulting sheet curvature
E = modulus of elasticity
I = area moment of inertia for the sheet,

and for a rectangular cross-section,

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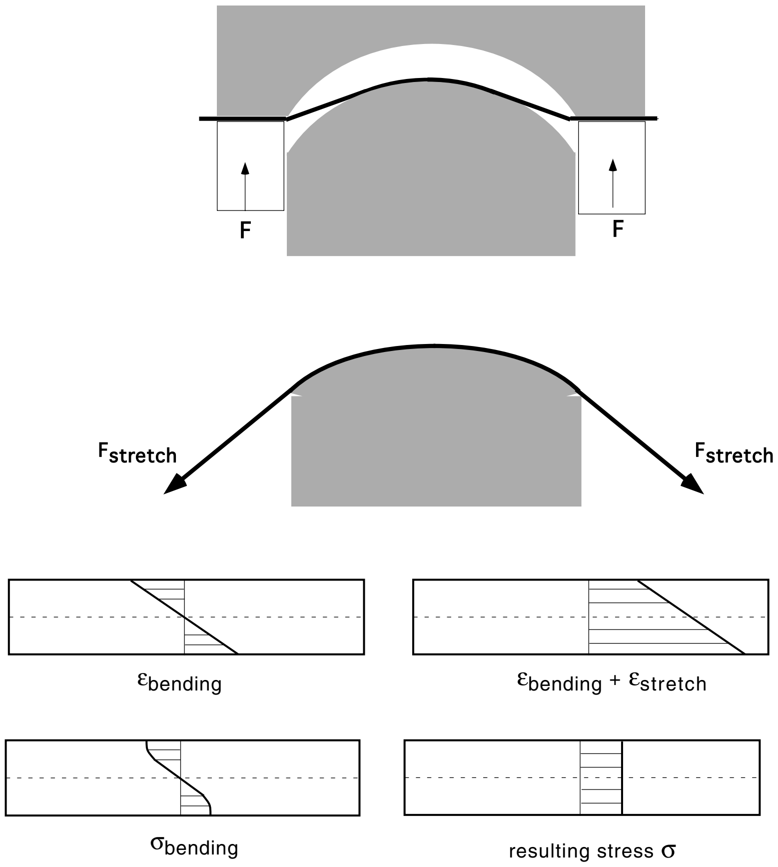

FIGURE 7.7 Simple two-dimensional draw forming with a blankholder and stretch forming. Notice the effect of adding stretch: the resulting stress distribution can become nearly uniform for a mildly strain-hardening material.

$$I = \frac{1}{12} bh^3 \tag{7.2}$$

where
b = width of the sheet
h = thickness of the sheet

As the beam curvature K increases, the bending moment will increase, and eventually the beam will begin to yield. When yielding occurs, the bending moment required for incrementally higher curvatures will decrease, and a moment–curvature relationship such as shown in Figure 7.8 will emerge. Just as with the tension example of Figure 7.4, the beam, when loaded to a maximum moment M_L, will elastically unload along a line of slope EI. The curvature springback ΔK will, as shown in the figure, be determined by the magnitude of this moment and the slope.

Consider now a very simple process where a sheet is formed between a matched set of cylindrical tools (see Figure 7.9). We are interested in the final curvature (K_U) of the part after the sheet is removed from the tools. The matched tools impose a fixed loaded curvature K_L on the sheet, which will load the sheet as shown in the figure. The amount of springback $\Delta K = K_L – K_U$ will depend on the maximum moment M_{max} and the slope EI according to

$$\Delta K = \frac{M_Y}{EI} \tag{7.3}$$

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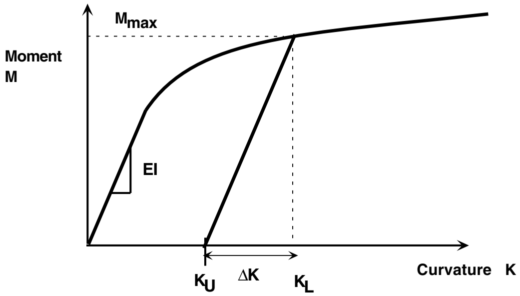

FIGURE 7.8 Generic moment curvature diagram showing curvature springback ΔK after unloading from the loaded curvature K_L.

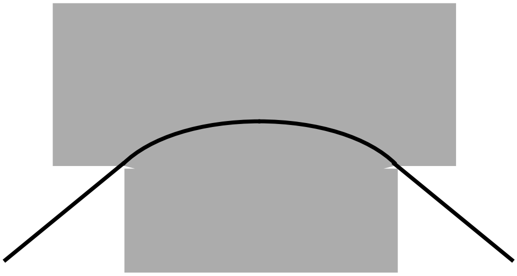

FIGURE 7.9 Simple matched tool forming over a cylinder. No edge constraint is used so the sheet sees only a bending moment if no interface friction is assumed.

Because the tooling imposes a fixed (input) curvature, the maximum moment (output) is determined by the constitutive relationship of the material, most importantly the yield stress and the thickness. The modulus E is most nearly constant, but the moment of inertia I varies with thickness to the 3rd power. Not surprisingly, in practice it is found the most sensitive parameters with respect to springback are the thickness, the yield stress, and the post-yield (strain-hardening) properties of the sheet.

7.2.2.1 Material Variations

The most common variations in sheet material are the thickness, yield stress, and plastic flow properties. The thickness can vary owing to rolling mill variations, and while some stock (such as aluminum beverage can stock) can be rolled to very low variations (~0.0002 in.), larger material can vary considerably. In some thicker material, and up into plates of thickness > 0.5 in., material specifications often call for only maintaining a minimum thickness for minimum service strength, but have a very broad tolerance on maximum thickness.

Perhaps more insidious from a process control perspective is variation of the constitutive properties of the sheet. If we imagine a linearly strain-hardening material, there are (at least) three parameters of concern: the elastic modulus E, the yield stress σ_Y, and the equivalent plastic modulus E_P. Because the modulus E depends primarily on the crystalline structure of the material, it is nearly constant for a given material independent of the particular alloy or working history. However, both σ_Y and E_P are very sensitive to the chemistry, heat-treating, and cold working history of the piece. Variations in σ_Y of up to 20% from supplier to supplier for a given alloy have been reported, although these quantities vary less within a given mill run or heat of material.

7.2.2.2 Machine Variation

Machine variations in forming are typical of most machine tools except that the loads and corresponding structural distortions are greater than most other processes. Forming loads of 10^3 or even

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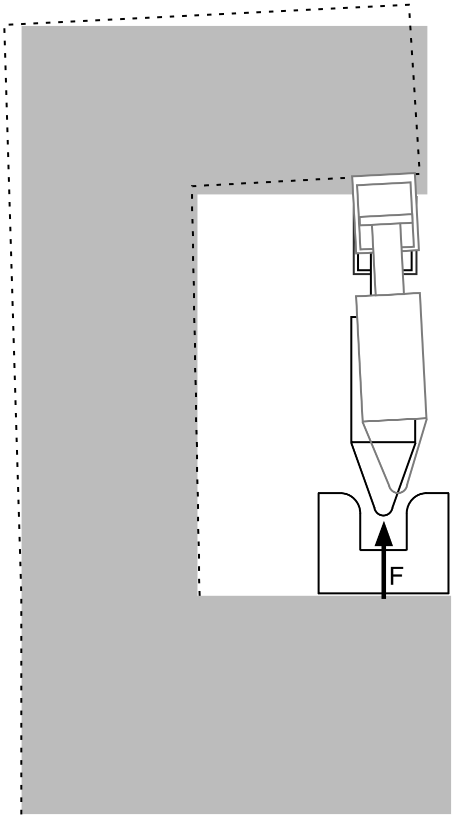

FIGURE 7.10 Simple closed-frame press shows the effect of sensor location on tool displacement control. $Y_{tooling} < A_{ctuator}$ because of stretching of the frame under the influence of the forming load F.

10^4 tons are not unusual with sheet and can be far greater for bulk forming. The elastic frames of the machine will deform with load, changing the relationship of the actuator displacements to the actual displacement of the tool–sheet interface.

Consider the situation shown in Figure 7.10. This shows the “C” frame typical of a pressbrake or stretch-forming machine. Clearly, the frame opening will stretch under load, and if the displacement sensor is collocated with the actuators, a load-dependent bias will always occur. It is also possible for the frame to bend as shown in the figure, further distorting the actuator–frame–tool geometry.

A similar collocation problem occurs with force measurement because of friction in the actuators and machine ways. If the forming force is measured at the actuator, or if as is often done, it is measured using the cylinder pressure in a hydraulic system, the actual forming force transmitted to the tooling will be attenuated by any static or sliding friction present. In general, it is wise to place the force sensor in or very near the tooling to avoid this problem.

7.2.2.3 Material Failure during Forming

In addition to controlling a process to achieve repeatable shape fidelity, it is also important that forming process control avoids situations where the workpiece will fail. Failure of sheet for bulk-forming processes is a complex phenomenon, and often failure avoidance can be no more than observing certain force or displacement limits on the machine.

Most failures occur either because of excessive tension in the sheet, causing it to tear, or excessive in-plane compression (from compound curvature shapes) which causes the sheet to wrinkle if unrestrained. Both forms of failure are difficult to detect. Tearing is preceded by localization of

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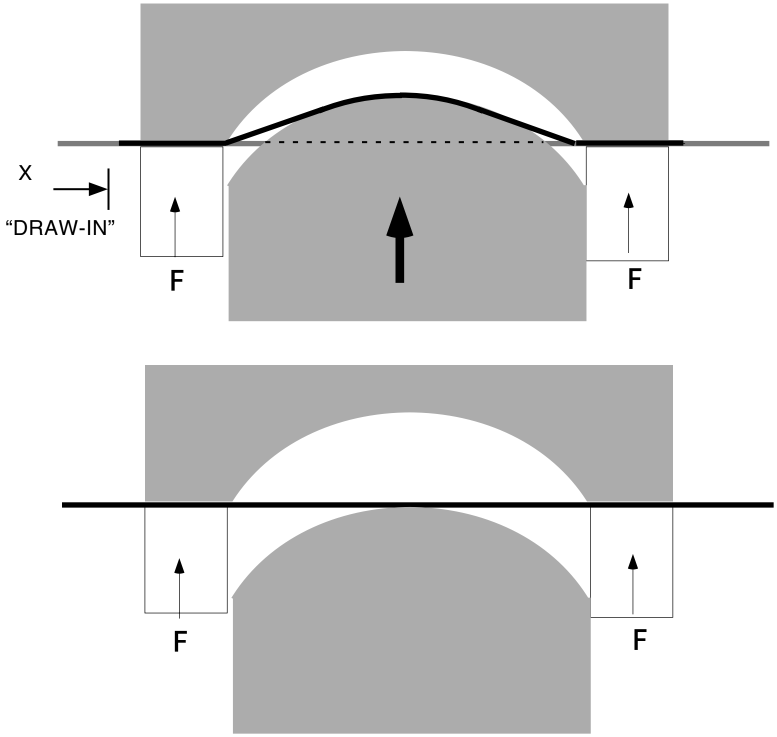

FIGURE 7.11 Simple draw forming with a frictional blankholder. As the tools move together, the sheet is drawn in an amount Δx.

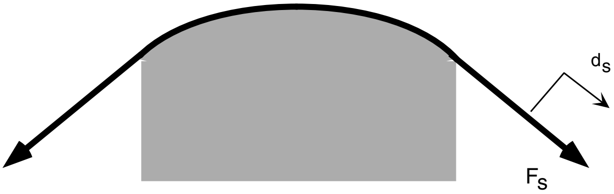

FIGURE 7.12 A stretch-forming process instrumented to measure force and displacement of the sheet during forming.

strain with attendant local thinning, and failure then occurs because of the resulting stress concentration. Wrinkling or buckling failure is even subtler because it often shows no detectable change in the force–displacement characteristics of the process. Instead, it can be thought of as an uncontrolled material flow (bucking) out of plane caused by in-plane compressive forces.

Active control to avoid failure is a complex topic both with respect to the mechanics of failure[1] and use of control to avoid these limits.[2–4] However, we can consider a simple example, that of stretch forming as shown in Figure 7.12. Here the stretch actuators are monitoring force (F_s) and displacement (d_s). As the process progresses, the resulting F–d curve for the actuators mimics the stress–strain characteristics of the sheet. By watching this curve develop, it is possible to determine the state of deformation and, for example, discover how close one is to the ultimate tensile strength of the material. In a more general case, the F–d data can be used as a process signature for which nominal trajectories are determined. Then, variations from these trajectories can be used to diagnose incipient failure.

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In some processes, such as the draw forming commonly used in automobile part production and in aerospace stretch forming, it is possible to measure the strain of the material directly using surface mounted gauges,[5] or by measuring the movement of the edge of the sheet as it is drawn into the tool.[6] In either case, the strain in the sheet can be used to estimate proximity to failure limits and control the process accordingly.

7.3 Machine Control

Historically, forming machines were used as a purely mechanical means to provide the large forces necessary, whether by using a slider crank or knuckle-type mechanism, or even more crudely, using high-momentum drop presses, to create the forming forces. However, with the advent of low-cost servo-control technology, most presses are now controlled by either motor-driven high-load leadscrews, or direct-acting linear hydraulic actuators with proportional servo valves.

The motor-driven leadscrews have the advantage of being mechanically simple, quieter, and often less expensive than hydraulics. In addition, the leadscrew, if the pitch is high enough, can isolate the actuator from the forming load in such a way as to nearly decouple the actuator dynamics from that of the load. However, leadscrew systems are typically limited to lower loads, owing to limits of the screw threads and nuts, and to lower velocities owing to the high pitches and wear on heavily loaded screw surfaces. Therefore, the vast majority of modern forming machines are hydraulically actuated and use either proportional servo-control of the actuators or a simple form of on–off control.

7.3.1 Sensors

As discussed above, there are many opportunities to measure either the forming machine or the workpiece itself. Because the most important constitutive relationship to forming is stress–strain or force–displacement, the latter two quantities are most often measured. In general, it is most practical to locate such measurements on the machine itself, independent of any part-specific tooling and the workpiece. However, as shown in Figure 7.10, it is always preferable to locate sensors as near to the workpiece as possible to mitigate the effects of machine distortion.

7.3.1.1 On Machine

For hydraulically actuated machines, the pressure in the cylinders can be measured and used as a surrogate force measurement if the cylinder area is known. For double-acting cylinders this area will be different depending upon the movement direction, and the cylinder seal friction as well as machine-bearing friction will add errors to this measurement. Load cells can be located either near the actuator–tool interface or in the machine frame itself. The cell must not add too significantly to machine compliance but must be sensitive enough to give useful force resolution over a large range for forces.

Displacements are most typically measured using cable-connected rotary sequential encoders. This allows for remote location of the encoder, and the cable can be stretched over long distances to ensure the correct displacement is measured. Such encoders commonly have resolutions far better than 0.001” and are noise free (except for quantization errors at very low displacements). The major design concern is that the cable be protected if it is near the forming region.

7.3.1.2 On Sheet

The ideal feedback measurement for forming would be the stress and strain fields throughout the sheet, preferably on each surface. With this information the local springback could be determined and failure prevented. Unfortunately, in-process measurements of stresses and strains are impractical. However, certain strains and correlates to strain can be measured. For example, in processes where substantial sections of the material remain free of surface pressures, optical or mechanical strain measurement devices could be inserted. Again, in practice, this has limited viability, but some

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examples have been tested in the aerospace industry[5] using surface mounted linear variable differential transducers (LVDTs). Optical measurement of surface strains is done regularly in material testing using video capture and measurement of circle grids on the surface of the sheet,[7] but it has not been used in volume production In this case, the surface strains can be used to directly control the extent of forming and, as was discussed in the earlier section on the process mechanics, controlling strains instead of stresses leads to a far more robust process.

In the draw-forming process, like that shown in Figure 7.11, the sheet is pulled against the frictional blankholder as the punch ascends into the die. The edge displacement of this sheet can be measured at one or more places, and if combined with knowledge of the punch displacement, can be used as an indirect indicator of strain.[2,6] However, for all but the simplest geometries this estimate will be crude at best. This measurement can be accomplished again with LVDTs but they are difficult to protect in the industrial environment. Instead, optical methods are preferred, though none are in practice at this time.

7.3.1.3 On Final Part

The ultimate measurement for control of forming processes is the actual final contour of the part. This allows full closure of the process loop as shown in Figure 7.3. All of the disturbances that enter the system, including material variations, press variations, and even machine controller variations (provided they are not entirely uncorrelated random signals) will be reflected in this measurement. However, such measurements have yet to be practical on an in-process basis, and are at best limited to use after the actual forming is complete. In addition, if complete part shapes are required, three-dimensional surface measurements are very time consuming, and can often take 10 to 100 times longer than the actual part processing time. This extended delay makes such measurements useless for in-process control, and they are better used for process diagnosis or some form of statistical process control.

New optical methods are under development[8] that may allow immediate post-process measurement, and with this innovation the delay may be short enough to allow effective part-to-part compensation. However, even if the measurement is made, for a general three-dimensional case the issue of limited control degrees of freedom or process resolution limits confounds full implementation of such a scheme.

7.4 Machine Control: Force or Displacement?

Each actuator in a forming machine can be placed rather easily under force or displacement feedback control. The design question then becomes: which is best? Of course, the answer depends upon the details of the process at hand, but there are some general observations that can be helpful in approaching this problem.

Consider the typical stress–strain curve in Figure 7.13. The implications of this curve are that at high strains (typical of forming) large variations in displacement cause small changes in force, and conversely, small variations in stress cause large variations in strain. This implies that we can most accurately relate both springback and incipient failure to strain, and it suggests that it is most logical to control displacement if given the choice. In addition, if the properties of the material change as shown in Figure 7.13, controlling the strain (displacement) would also be less sensitive to this variation than controlling the stress (force).

Indeed, it is best to control the true sheet strain if possible, but as discussed above it is usually not feasible. The substitute is to control displacement of the tooling and try to relate that to strain. Herein lie several problems. First of all, the single lumped machine displacement variable must be related to a specific point strain, and on complex three-dimensional parts, the strain field can be highly varied. Second, the machine will always have uncertainties caused by both the frame deflections mentioned earlier and by mechanical backlash in the frame and actuators. Third, in processes such as stretch forming, the sheet is loaded manually and the force–displacement “zero

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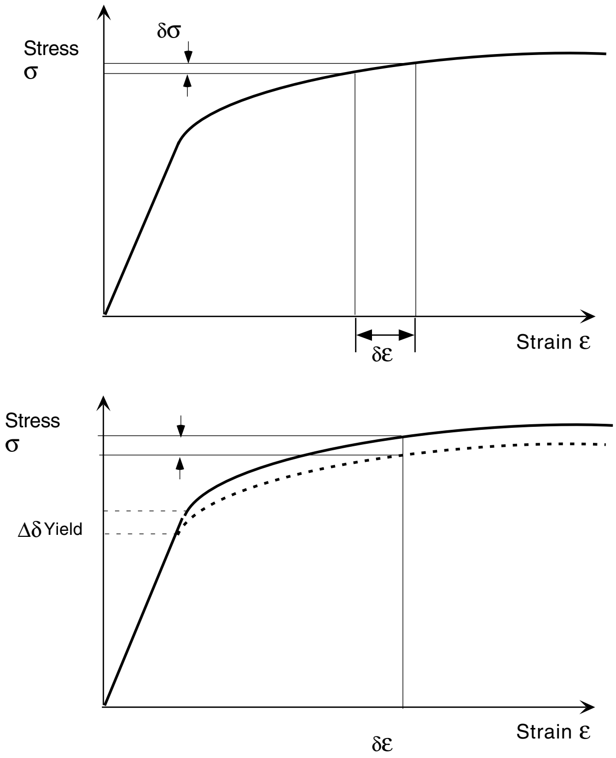

FIGURE 7.13 Stress–strain sensitivity at high strains.

point" may be highly variable. For these reasons alone displacement control is prone to large errors, despite its apparent robustness with respect to force and material property variations.

However, when looking at specific classes of processes, the question becomes a bit easier to answer. For the brakeforming process shown in Figure 7.6, none of the above concerns is present, and indeed all such machines are displacement controlled to give a more robust performance when material properties change. However, from the geometry in Figure 7.6 it should be apparent that changes in the thickness of the material introduce a displacement bias. (A novel method for in-process determination of the thickness is possible using both force and displacement measurements. By tracking the initial F–d curve, the actual zero point can be extrapolated from the data and used to determine appropriate command bias.)

In contrast to brakeforming, consider again the matched tool-forming process shown in Figure 7.9. In this case, displacement control would be very dangerous if the exact thickness of the material is unknown or the tooling locations had some uncertainty. In simple terms, the problem is between the extremes of never fully forming the part or bottoming the tooling and creating excessive tool surface forces. Therefore, for this process, active force control or displacement control into a compliant cushion (effectively a form of force control) is preferred.

7.5 Process Resolution Issues: Limits to Process Control

If we consider controlling part shape to be the ultimate goal of our process, then it is important to evaluate the ultimate ability of the process to vary the shape under some form of process control. This requires that the resolution of the process — the relationship between the actuator degrees of freedom and the degrees of freedom required by the part shape — be determined.

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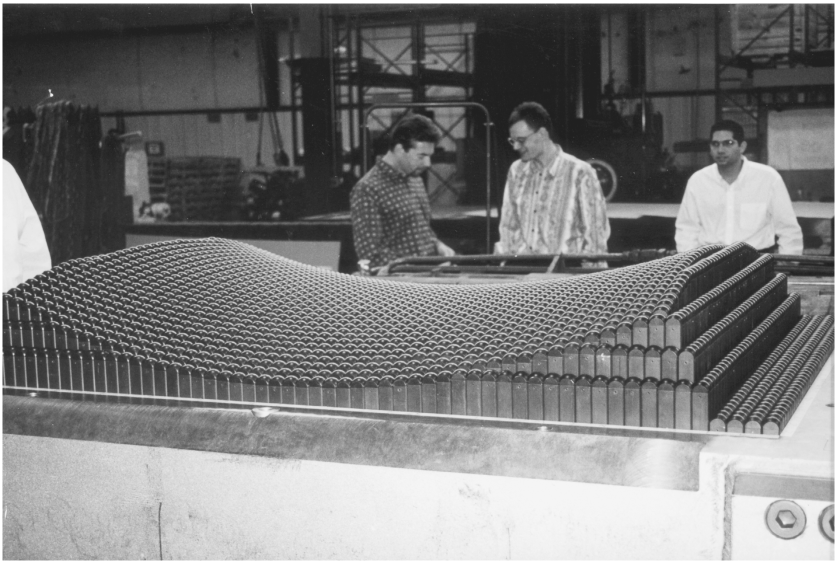

FIGURE 7.14 Photo of a prototype reconfigurable stretch-forming tool. The tool is comprised of > 2600 individual servo-driven pins with spherical ends.

There is a natural diffusion of the lumped forming energy provided by the tooling to the inherently distributed energy necessary to create a general three-dimensional deformation. This physical fact emphasizes the most important control impediment in forming processes. Because control is most easily exerted on lumped power variables on the machine (e.g., actuator forces or velocities/displacements) the effect of this control is diffused over the entire workpiece by the tooling. As a result, the effect of the lumped controls on the final part shape is indeterminate and well outside the control loop. Instead, the control system is merely providing a highly consistent level of bulk energy to the tool, which will, in turn, distribute the energy according to the local constitute relationships of the tool and workpiece. The only solution to this dilemma is to add the energy distributor degrees of freedom (the tool) to the control system. This can be done only by adding spatial degrees of freedom such as programmable or movable die surfaces, or by taking three-dimensional parallel forming processes and doing them in a series of two-dimensional stages. The former has been accomplished, for example, by using discrete tools whose elements can be moved in real time, and the latter is exemplified by processes such as roll forming.

7.5.1 Process Resolution Enhancement

It is worthwhile to close with some leading edge examples of how control can be extended beyond the classical machine servo controllers commonly found on production machinery to include some reflection of the sheet-forming process itself. Perhaps the two most interesting examples are attempts to control the strain in a complex three-dimensional draw-forming process and attempts to use a tool whose shape can be rapidly reprogrammed between forming cycles.

The process resolution discussion makes it clear that the main degrees of freedom with respect to part shape are contained in the tool shape itself. If the tool can be changed only by actual addition or subtraction of material, this can hardly be called process control. However, if the tool surface is in some way programmable, then the process resolution can be greatly increased. An example of such a tool[10–12] is shown in Figure 7.14 where the tool surface is comprised of many individually controllable "pins" that form a discrete surface. This surface is then smoothed by a polymer pad and can be used to form commercially acceptable parts.

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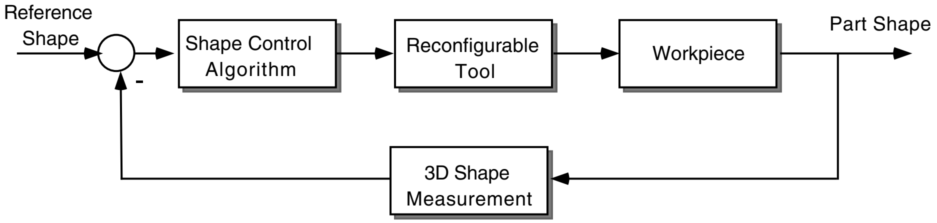

FIGURE 7.15 Shape control system using a reconfigurable tool and spatial frequency controller.

Other forms of resolution enhancement have been proposed. These include a sheet blankholder (see Figure 7.7) that is either broken into independently controllable segments so that the frictional restraining force can have several discrete values around the periphery of the sheet, or a deformable blankholder with variable displacement supports[10] that allow a continuously variable (but spatially band-limited) blankholder pressure distribution.

7.6 Direct Shape Feedback and Control

The special case shown in Figure 7.3 of direct feedback of part shape has recently found pre-commercial application to stretch forming in the aerospace industry.[11] In this system the reconfigurable tool of Figure 7.14 is combined with a novel three-dimensional shape-sensing device and a spatial frequency-based control law[11–13] to actuate the tool until shape errors are minimized (see Figure 7.15). The actual control system has a minimum one forming cycle delay built in because the part cannot be measured until after forming.

7.7 Summary

Control of metal-forming processes has advanced considerably with the advent of inexpensive computer servo controls. However, the inherent sensitivity of the process to variations in the constitutive properties of the workpiece materials prevents simple servo control of machine variables from fully controlling the process output. Such control does, however, greatly reduce the process variability, and with good production control of material and proper maintenance of the machine and tooling, highly consistent and accurate parts can be produced at high rates. To move to the next level of control where either the strains or final shapes are actively controlled involves a large jump in sensing, actuation, and control law technology that has yet to emerge on the production floor.

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