CHAPTER 3

FUNDAMENTALS OF BENDING

3.1 GENERAL

Metal forming is a near-net-shape manufacturing process by which various components used for automobiles and air craft industry are made from sheet metal. Bending is the plastic deformation of metals about a linear axis called the bending axis with little or no change in the surface area. Bending types of forming operations have been used widely in sheet metal forming industries to produce structural stamping parts such as braces, brackets, supports, hinges, angles, frames, channel and other nonsymmetrical sheet metal parts (George E Dieter 1988).

Press brake forming is a process in which the sheet material is placed over an open die and pressed down into the die by a punch. The primary advantages of the press brakes are versatility, the ease and speed with which they can be changed over to a new setup and low tooling costs. Press brake forming is applicable to any metal that can be formed by other methods, such as press forming and roll forming. Low carbon steels, high strength low alloy steels, stainless steels and aluminum alloys are formed in press brakes. It is necessary to select the proper bending method in accordance with the application and function of the product.

One of the important characteristics noticed during the bending operation is that the tensile stress decreases toward the centre of the sheet
thickness and becomes zero at the neutral axis whereas the compressive stress increases from the neutral axis towards the inside of the bend as shown in Figure 3.1. Even with large plastic deformation in bending, the central region (elastic metal band or zone) of the sheet remains elastic and on unloading, elastic recovery occurs.

![Stress Distributions in Bending](image)

**Figure 3.1  Stress Distributions in Bending (Courtesy-ASM Hand Book)**

### 3.2 AIR BENDING PROCESS

Air bending is the simplest bending process commonly used in automotive stamping and fabrication industries. In the fabrication industry, one of the critical challenges is to maintain close geometric tolerance in finished products.

In the air bending (three point bending), the required angle is produced on the workpiece by adjusting the depth to which the punch enters the die opening and it is shown in Figure 3.2. This permits the punch to overbend the metal sufficiently to produce the required angle after springback, thereby compensation is achieved. It can be considered as a flexible process. In other words, this process allows obtaining a wide interval of bent parts.
Figure 3.2 Schematic of Air bending (Courtesy-Ohio State University)

With the same tool configuration, different bend angles are obtained as well as different curvatures or curvature radius. The change in the size of die opening also changes the amount of load needed to make the bend. As the die opening increases, lesser force is required and as the die opening decreases, the bending leverage is less and more force is required.

The advantages of the air bending process are

- The variety of angles that can be done with a minimum number of punches and dies.
- The easy control and compensation of springback are possible.
- As less force is required, small capacity press is sufficient, preventing excessive strain on the press brake.
The disadvantages of the air bending process are

- The possible inconsistency is evident in the bends because of variations in dimensions and temper of the work metal as it is received from the mill.
- Springback in the air bending process is large because of the absence of bottoming.

Some important issues in bending are minimum bending radius, springback, bend force and anisotropic properties of the sheet.

### 3.3 SPRINGBACK

In order to increase the efficiency of production and to improve the quality of the products, many researchers have been working in the area of springback. During the bending process, the metal on the outside of the bend radius is stretched and the metal on the inside is compressed. This means that the metal near the neutral axis may be stressed to values below the elastic limit and the metal far away from the neural axis may be stressed beyond the yield stress. When the bending load is removed, the elastic deformation tends to return to the original configuration but is restricted by the plastic deformation zone. The stress distribution changes until plastic and elastic zone inside the deformed sheet comes to the equilibrium. This final configuration change is known as springback. In other words, springback or elastic recovery refers to the shape discrepancy between the fully loaded and unloaded configurations.

The stress-strain plot shown in Figure 3.3 illustrates the springback phenomenon. Upon unloading in a bending process there is an elastic recovery, which is the release of the elastic strain and the redistribution of the residual stresses through the thickness direction, thus producing springback.
Springback causes changes in shape and dimensions that can create major problems in the assembly. Hence springback prediction is an important issue in sheet metal forming industry.

![Stress vs Strain Diagram](attachment:stress_strain.png)

Figure 3.3 Loading Diagram and Springback (Courtesy-ASM Hand Book)

### 3.3.1 Factors Affecting Springback

Many factors could affect springback in the process, such as sheet material properties (thickness of the sheet, strain hardening exponent, strength coefficient, tensile strength), the tool geometry (punch radius, die radius, die opening) and process parameters (bending angle, punch travel, punch velocity and lubrication).

Some of the methods for compensating the springback angle are listed below:

- By bending the part to smaller radius of curvature than is desired. ie, by over-bending the part so that the part dimension after springback is the needed dimension.
• By bottoming the die to produce a coining action.
• By using high temperature forming process to reduce yield stress.

3.3.2 General Observations of Springback

• Springback increases with the yield stress or the strength coefficient, strain hardening exponent and plastic strain ratio, since higher these values the greater is the resistance to plastic yielding.
• Springback decreases with the elastic modulus because the resistance to elastic bending increases with Young’s modulus.
• Bending of a thin sheet with larger bend radius enhances springback.
• The springback angle increases linearly with the bending angle.
• Wide sheet bending for plain strain conditions has a larger springback than narrow sheet bending.

3.3.3 Springback Ratio \( (\Delta \theta / \theta) \)

Elastic recovery after unloading causes the springback phenomena. It is assumed that the unloading moment \( \Delta M \) and applied bending moment \( M \) have the same magnitudes but opposite sign. Samuel (2000) elsewhere proposed springback ratio as follows

From the elastic deformation of unloading

\[
\Delta \sigma = E' \Delta \varepsilon_0
\]  

(3.1)
\[ E' = \frac{E}{1 - \gamma^2} \] under the plane strain condition

where \( \Delta \sigma \) - Strain increment
\( E' \) - Plastic Young’s Modulus
\( E \) - Young’s Modulus
\( \gamma \) - Poisson’s ratio

\[ \Delta \varepsilon_\rho = \left( \frac{\eta}{\rho} \right) - \left( \frac{\eta}{\rho^*} \right) \]  

(3.2)

where \( \Delta \varepsilon_\rho \) - Effective strain increment
\( \eta \) - Radial distance from the origin
\( \rho \) - Neutral axis before unloading
\( \rho^* \) - Neutral axis after unloading

For simplicity, the elementary bending theory is adopted to analyse the deformation of elastic unloading.

Unloading moment \( \Delta M = 2w \int_0^{\pi/2} \Delta \sigma_\rho \eta \, d\eta \)

\[ = \frac{wEt^3}{12(1 - \gamma^2)} \left( \frac{1}{\rho} - \frac{1}{\rho^*} \right) \]  

(3.3)

where \( w \) - Width of the sheet
\( t \) - Thickness of the sheet

Assuming \( \sigma_e = (1 + \eta)\bar{\sigma}_e \) as a constant
Applied bending moment = \[ \left( \frac{1+R}{\sqrt{1+2R}} \right) \left( \frac{\sigma_e}{1+n} \right) \left( \frac{wt^2}{4} \right) \] (3.4)

where

- \( R \) - Normal anisotropic value
- \( \sigma_e \) - Effective stress
- \( \bar{\sigma}_e \) - Mean effective stress
- \( n \) - Strain hardening exponent

\[ \approx K \left[ \frac{1+R}{\sqrt{1+2R}} \right]^n \left[ \frac{t}{2\rho} \right]^n \] (3.5)

where

- \( K \) - Strength coefficient

For elastic recovery of unloading \( \Delta M = M \)

\[ \frac{1}{\rho} - \frac{1}{\rho^*} = K \left( \frac{1+R}{\sqrt{1+2R}} \right)^{1+n} \left[ \frac{3(1-\gamma^2)}{2E} \left( \frac{t}{2\rho} \right)^n \right] \] (3.6)

\( \rho \theta = \rho^* \theta^* \), The above equation can be written as

\[ \frac{\Delta \theta}{\theta} = \left( \frac{1}{\rho} - \frac{1}{\rho^*} \right) = K \left( \frac{1+R}{\sqrt{1+2R}} \right)^{1+n} \left[ \frac{3(1-\gamma^2)}{2E(1+n)} \left( \frac{t}{2\rho} \right)^n \right] \] (3.7)

where

- \( \Delta \theta \) - Difference of the angle before and after unloading in bending
- \( \theta \) - Experimental bend angle under load.
For simplicity, the elementary bending theory is adapted to analyse the deformation of elastic unloading.

### 3.4 Bend Force

The bend force calculation provides a base for choosing appropriate press machines and designing dies. The bend force depends on sheet material properties (thickness of the sheet, width of the sheet, strain hardening exponent, strength coefficient, tensile strength), the tool geometry (punch radius, die radius, die opening) and process parameters (bending angle, punch travel and the friction coefficient). The maximum external bending moment generally depends on the type of bending and the bending tool geometry. It consists of two categories,

- The bending moment due to bend force and punch travel
- The additional work due to friction around the die shoulders/punch. This friction loss would be higher without lubrication, and this loss increases as the bending angle increases or the punch travel increases.

The bend force increases with increasing width, thickness of the sheet and die friction, and it decreases with increasing die opening and punch radius. A higher bend force is required for sheets with higher strength, strain hardening and normal anisotropy. The bending arm in air bending is determined by the contact points on die radius and on punch tip. Therefore, the bending moment and the bend force are related to die radius. The maximum bend force (Ohio State University) can be determined by

\[
F = \frac{L L^2 (UTS)}{W_d}
\]  

(3.8)
where \( F \) - Force required bending
\( L \) - Length of the sheet
\( t \) - Thickness of sheet
\( UTS \) - Ultimate tensile strength
\( w_d \) - Die opening.

This equation is widely used in industrial environments to calculate the maximum bend force.

### 3.5 ANISOTROPY

In sheet metal forming, incorporating material anisotropy is important for making accurate predictions. During the rolling process and the subsequent annealing, the grains and any inclusion present become elongated in the rolling direction and a preferred crystallographic orientation develops. This causes a variation of properties with direction. The dependence of properties on orientation is called anisotropy. The anisotropy causes different flow stress with respect to the orientation angle that is measured from the rolling direction. The different flow stresses have significant effects on the bending process. Phenomenologically, the anisotropy is characterized by different strain hardening responses for different orientations.