1. Identify the three basic types of sheet metalworking.
Cutting, bending and drawing.

2. How should the clearance be applied to a round punch and die in blanking?
*The die size equals the blank size, and the punch is smaller by twice the clearance. For best results, the clearance is typically between 4 and 12% of sheet thickness (smaller clearances are associated with more ductile sheet materials).*

3. Circular blanks of diameter = 200 mm are to be cut from h = 3 mm thick, annealed 5052 aluminum alloy with tensile strength 190 MPa. a) What would be appropriate punch and die dimensions? b) What press force is needed?
a) As the aluminum is in the annealed condition, it is soft and ductile. Per question #2, a clearance of 5% of the sheet thickness would be a good approximation, or 0.05(3 mm) = 0.15 mm. The die dimension should be 200 mm, and the punch diameter = 200 mm – 2(0.15 mm) = 199.70 mm.
b) Shearing Force = Shear strength of the material x material thickness x length sheared. The press force is the shearing force, and the shear strength of metals is approximately 70% of their ultimate tensile strength. Thus the minimum press force required = 0.7(190 MPa)(3 mm)(200)(π) = 251 kN. It is typical to allow another 20% larger press than the minimum calculated, thus a 300kN press would be appropriate for this job.

4. An AKDQ steel blank (LDR = 2.4) of 200 mm diameter and 2 mm thickness is to be drawn into a cylindrical cup of 100 mm internal diameter. The tensile strength of the sheet is 320 MPa. Determine whether the draw is feasible, and if so, estimate the required press force.
The Limiting Drawing Ratio (LDR) is empirically determined for sheet materials, so the 2.4 LDR came from published data for AKDQ steel. If the drawing ratio (ratio of blank diameter to punch diameter) for the proposed operation is less than the LDR for the material, the draw is feasible. For this case, the draw ratio is 200 mm/100 mm = 2, so the draw is feasible.
The required press force in drawing operations can be estimated as:

\[ [(\pi)(D_p)(h)(UTS)] \times [(d_o/D_p) - 0.7] \]

where \( D_p \) is the punch diameter, \( d_o \) is the blank diameter, \( h \) is the sheet thickness, and \( UTS \) is the tensile strength of the sheet. Press force then equals:

\[ [(\pi)(100 \text{ mm})(2 \text{ mm})(320 \text{ MPa})] \times [200 \text{ mm/100 mm} - 0.7] = 261 \text{ kN} \]

5. What is anisotropy and how can it be expressed quantitatively?
Anisotropy in materials means that the mechanical properties are not equivalent in all directions. This condition is typically found in rolled sheet because the strains in the length (rolling direction), width and thickness are not uniform (recall the plane strain assumption in lab). A common quantitative measure of
anisotropy in sheet metals \( (r) \) is the ratio of strain in the width direction to strain in the thickness direction:

\[
 r = \frac{\varepsilon_w}{\varepsilon_t}.
\]

6. Wrinkling, earing, and cup bottom fracture are common occurrences in cup drawing. What are the typical causes?

Wrinkling (and wrinkling with bottom fracture) is typically caused by insufficient blank holder force, earing is caused by planar anisotropy in the sheet, and cup bottom fracture (with no wrinkling; upside-down hat shape) is caused by excess blank holder force.

7. What is “springback” in sheet metal bending?

Elastic recovery of the sheet metal after bending; usually measured as the difference between the final included angle of the bent part and the angle of the tooling used to make the bend, divided by the angle of the tooling.

8. Why are true stress and strain generally of more interest to manufacturing engineers than engineering stress and strain?

Engineering stress and strain are adequate for describing the behavior of materials in the elastic regime, and design engineers are interested mostly in the modulus of elasticity and yield strength – behavior prior to necking (instability) in the uniaxial tensile test. Manufacturing engineers are more interested in plastic deformation, strain hardening, and the limits of the ductility and flow of a material – or behavior subsequent to necking. These properties are best described using true stress and strain and the flow stress equation, \( \sigma = K \varepsilon^n \). True stress and strain also are valid in compression, whereas engineering stress and strain are not well defined in compression.

9. In the flow stress equation, \( \sigma = K \varepsilon^n \), what do the values of \( K \) and \( n \) indicate?

\( K \) is the strength coefficient, and is the stress at a strain of unity. “\( n \)” is the strain hardening exponent, or the slope of the line on a linear scale. A higher value of \( n \) generally indicates a more ductile material.

10. What problems in sheet metal forming process and product design are often addressed using computer-aided modeling and simulation techniques?

Determination of springback, blank holder forces, thinning, wrinkling, and the determination of press loads are common issues addressed by computer simulation on complex sheet metal components.
Bulk Forming/Forging

1. Distinguish between cold, warm, and hot forming.

By definition, cold (and warm) forming operations are performed below the recrystallization temperature of a metal; hot work is done above the recrystallization temperature. This means that cold and warm formed metals will strain harden during forming. Conversely, hot worked metals will very quickly recrystallize anneal as hot working progresses, and generally will exit the forming process in a relatively soft condition.

Cold and hot forming operations are not related to ambient temperature. As a thought provoking example, the recrystallization temperature of Pb is actually below room temperature, so bulk forming of Pb at room temperature is technically a hot working operation. Alternately, bulk forming of Cu at room temperature (below its recrystallization temperature) is technically a cold working operation.

However, as metals are heated, their flow stress decreases and they generally become more ductile – even below their recrystallization temperature. To take advantage of this improved ductility, some metals that are difficult to form at room temperature are heated to some temperature above room temperature, but below their recrystallization temperature, and “warm” formed.

2. What factors strongly influence effective flow stress in bulk forming operations?

Effective flow stress is a function of total effective strain, strain rate, and temperature.

3. Consider cold heading a nail starting with \( D_0 = 3/16 \) inch diameter low carbon steel wire, assuming no friction (well-lubricated dies), and a final head diameter \( D_f = 3/8 \) inch. The flow curve parameters for the steel are \( K = 80,000 \) psi, \( n = 0.24 \). Find the maximum force required during the operation.

\[
\varepsilon = \ln(A_f/A_0) = \ln(0.110/0.028) = 1.38
\]
\[
Y_f = 80,000 \times (1.38)^{0.24} = 86,430 \text{ psi}
\]
Force = 86,430 psi \((0.110 \text{ in}^2) = 9507 \text{ pounds or } 4.75 \text{ tons}

Sample Questions –Forging and Sheet Metal Forming
1.) ______ Which of the following falls into the hot working temperature range relative to the absolute melting temperature of the given metal being formed?
   a.) room temperature
   b.) 0.2 Tm
   c.) 0.4 Tm
   d.) 0.6 Tm

2.) ______ Increasing the strain rate during hot forming tends to have which of the following effects?
   a.) Has no effect
   b.) Increases flow stress
   c.) Decreases flow stress
   d.) Increases fracture toughness

3.) ______ The maximum draft in a rolling operation depends on which of the following?
   a.) Coefficient of friction between rolls and strip
   b.) Material thickness
   c.) Strain hardening exponent of the material
   d.) Rolling speed

4.) ______ The three basic sheetmetal forming operations include all of the following except:
   a) bending
   b) cutting
   c) drawing
   d) brazing

5.) ______ The harder the sheet metal being cut,
   a) the smaller the recommended clearance
   b) the larger the recommended clearance
   c) the higher the likelihood you will need a kryptonite tool
   d) the shorter the cycle time

6.) ______ Cutting force required for a blanking operation is most closely related to what material property?
   a) yield strength
   b) ultimate strength
   c) shear strength
   d) modulus of elasticity

7.) _____ Which of the following processes is NOT a bulk deformation process?
a) extrusion  
b) deep drawing  
c) forging  
d) rolling

8.) _____ Sheet metal parts are typically characterized by:
   a) high heat generation  
b) high surface area to volume ratio  
c) high density alloys  
d) high ho, high ho, I really just don’t know

9.) _____ Hot working metals refers to the following temperatures relative to the melting point of the given metal on an absolute scale?
   a) room temperature  
b) 0.2 Tm  
c) 0.4 Tm  
d) 0.6 Tm

10.) _____ In rolling, the maximum draft depends on all of the following except?
    a) roll diameter  
b) coefficient of friction between the rolls and the stock  
c) stock thickness

11.) _____ In rolling, the point at which the speed of the workpiece is the same as the speed of the rolls is called what?
     a) equilibrium point  
b) slip ratio  
c) neutral point  
d) necking point

12.) _____ The property that causes hot-forged metals to exhibit different flow stresses at different forming speeds is known as?
     a) forming speed factor  
b) strain rate sensitivity  
c) strain hardening  
d) hot working stress factor

13.) _____ The change in thickness of a workpiece going through a rolling mill is called the __________.
     a) reduction  
b) rolling ratio  
c) draft  
d) slip

14.) _____ Which of the following is NOT one of the basic sheet-metal forming operations?
     a) bending  
b) cupping  
c) deep drawing  
d) cutting

15.) _____ Which of the following is NOT a common defect in sheet metal parts?
     a) wrinkling  
b) bowing  
c) earring  
d) tearing
16.) In a punching operation, it is desired to create a hole that is 0.500" in diameter. Which of the following is true?
   a) the punch diameter should be (0.500" - clearance)
   b) the die diameter should be (0.500" - clearance)
   c) the punch diameter should be 0.500"
   d) the die diameter should be 0.500"

17.) Forming a the paper for a cupcake cup is most similar to:
   a) Stretch forming
   b) Stretch flanging
   c) Shrink flanging
   d) Spinning

18.) Complex parts are frequently hot forged because
   a) Better surface finish than cold forging
   b) Recrystallization prevents strain hardening
   c) Tooling is less expensive than cold forging
   d) Production rates are higher than for cold forging

19.) On a forming limit diagram (FLD) the lowest strain at failure always occurs under:
   a) Uniaxial tension
   b) Equal biaxial tension
   c) Equal tri-axial tension
   d) Plan strain

Match the Description on the left with the most appropriate process on the right (Use each answer only once.)

___ Hammer
___ Ammunition
___ Large aluminum cooking pot
___ Guardrail (side of road)
___ Car Door Panel
___ Baking Pan

A. Deep Drawing
B. Roll Forming
C. Forging
D. Spinning
E. Stamping
F. Stretch Forming

True / False
20.) T / F Flat rolling is a bulk deformation process
21.) T / F Average flow stress is the true stress divided by (1+n)
22.) T / F Hot working at high forming speeds requires more force than at low speeds
25.) T / F The flow stress curve applies only to material in the elastic deformation region

For each of the following machines, select the appropriate answers (circle one per cell)

<table>
<thead>
<tr>
<th>Press Type</th>
<th>Press is Energy Limited?</th>
<th>Press is Force Limited?</th>
<th>Press stall is bad?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drop Hammer</td>
<td>T / F</td>
<td>T / F</td>
<td>T / F</td>
</tr>
<tr>
<td>Mechanical Press</td>
<td>T / F</td>
<td>T / F</td>
<td>T / F</td>
</tr>
<tr>
<td>Hydraulic Press</td>
<td>T / F</td>
<td>T / F</td>
<td>T / F</td>
</tr>
</tbody>
</table>

Problems:
27.) [12%]
An upsetting platen performs a hot working operation. The platen moves at 20 ft/sec and deforms a material with a starting height of 2 inches. If the material being upset has a strength constant of 20 ksi and a strain rate sensitivity exponent of 0.3, calculate:

a.) the strain rate of the operation when the platen first comes into contact with the workpiece,
b.) the flow stress induced in the workpiece.

28.) [15%]

A hot rolling mill has rolls of Radius = 10 in. It can exert a maximum force of 250 tons. (1 ton = 2000 lbf)
The mill has a maximum horsepower = 100 hp. It is desired to reduce a 1 in plate by the maximum possible draft in one pass. The starting plate is 10 in wide. In the heated condition, K=20 ksi, n=0. Determine:

a.) maximum possible draft

b.) true strain at maximum draft

maximum speed of the rolls for the operation
24.) [10%]
A square hole, 1” on each side is to be made in a workpiece during a punching operation. The material is 0.040” thick. The recommended clearance allowance for the specified material is a=0.050.
   a.) What is the clearance? __________________
   b.) Indicate the correct punch and die dimensions on the drawing below.
   c.) If the material has an ultimate tensile strength of 40 ksi, estimate the punch force required for this operation?

![Diagram of punching operation]

25.) [10%] You are performing a drawing operation to form a 5” diameter cup. The blank size is 10”.
   a.) What is the drawing ratio?
   b.) What is the reduction?

1.) [10%] You are conducting a cold rolling operation. The material you are using has properties of: K=58 ksi, n=0.16. The incoming material is 0.75 in thick by 10 in wide and is reduced to 0.50 in thick in a single pass. The rolls are 12” diameter. (Note: assume plane-strain condition)

   Calculate
   a.) the draft
   b.) the average flow stress
   c.) the roll force required
You are studying the forging of a round bar with the given dimensions and material properties. The direction of compression is along the axis of the bar.

Geometry
Initial Diameter = 1.5”
Initial height = 2.0”
Final height = 0.75”
Strain rate = 20 /sec

Material Properties:
K = 65 ksi
n = 0.2
C = 18 ksi
m = 0.5

Determine the following based on the above information.

a.) Average diameter of the rod after being forged
b.) True strain at the end of the process
c.) Peak force required to cold forge the rod
18). [25%] You have a punch tooling with three punches. Each punch is a different length. The punches are as follows:

<table>
<thead>
<tr>
<th>Punch Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Punch Profile</td>
<td>2” Square</td>
<td>3” circle</td>
<td>2” circle</td>
</tr>
<tr>
<td>Punch length</td>
<td>4”</td>
<td>4.5”</td>
<td>5”</td>
</tr>
</tbody>
</table>

The metal that is being punched is a sheet of low-carbon steel with an ultimate tensile strength of 47ksi and a thickness of 0.125”. Based on the information given:

1.) Calculate the force required for each punch individually.
2.) Calculate the peak force per stroke that the press will have to develop to punch the sheets with the given punches.
3.) Draw a rough sketch of the punch force vs. stroke for the process.
4.) What would be the required press force if all of the punches were the same length?
1 hp = 396,000 in-lbf/min
1 ton = 2000 lbf

\[ A = [d(D-d)]^{0.5} \]

\[ c = a t \]
\[ d = t_0 - t_f \]

\[ D_c = D_p + D_p S + D_p S^2 \]

\[ DR = D_p/D_p \]

\[ F = 0.7 TS t L \]

\[ F = Y f \w L \]

\[ f_i = N n_i f \]

\[ K = 3.333 \times 10^{-6} \text{ joule/(mm}^3 \text{ kelvin)} \]

\[ L = [R(t_o - t_i)]^{0.5} \]

\[ MRR = w d f_i \]

\[ N = v / (\pi D) \]

\[ P = 2 \pi N F L \]

\[ P = F_c v \]

\[ Q_b = p \pi D d_c^3 \sin^2(A) / (12 \eta L) \]

\[ Q_d = 0.5 \pi^2 D^2 N d_c \sin(A) \cos(A) \]

\[ Q_s = Q_d Q_b \]

\[ r = (D_h - D_p) / D_h \]

\[ r = d/t_0 \]

\[ s = (v_f - v_i) / v_i \]

\[ T = 0.5 F L \]

\[ t_0 w_o L_o = t_i w_i L_f \]

\[ t_0 w_o v_0 = t_i w_i v_i \]

\[ T_m = (L + A) / f_i \]

\[ U = P / MRR \]

\[ U_m = K T_m^2 \]

\[ Y_f = K \varepsilon^m / (1 + n) \]

\[ Y_f = C \varepsilon \]

\[ Y_f = K \varepsilon^a \]

\[ \varepsilon = \ln (t_f/t_i) \]

\[ \varepsilon = v/h \]