Cutting, which includes shearing, is the most common pressworking operation. A single formed stamping such as a sieve or automobile inner door has many holes, all of which are produced by cutting operations. In the case of the sieve, which has many holes in a regular pattern, the process may be referred to as perforating. However, in each example, the same cutting process employed to produce a single hole is used.

The repair and troubleshooting of cutting dies is a very important die repair skill. The work varies from maintaining simple hole punching dies to complex progressive and transfer dies performing many metal forming operations in addition to cutting and shearing.

**Understanding Important Concepts and Skills**

Effective die maintenance starts with the die designer. If the die is designed correctly it will work correctly and require infrequent repairs that are simple. This chapter starts with the basics that all diemakers and designers most likely understand. However, this book serves as a reference for persons starting in the trade as well as experienced workers including engineers. It must serve the needs of the apprentice and trainee as well as those with decades in the trade as a source of information to solve problems.

![Figure 1](image)

*Figure 1*. Sectional views of a cutting die (A) for producing a round hole. The punch is compressed (B) after making initial contact with the stock. *Smith & Associates*
Example of a Simple Die for Punching A Round Hole
Figure 1A illustrates a sectional view of a simple die for punching a hole in a part. Such dies may have several punches. In addition, a cut off shearing operation may be included if the die is fed with strip or coil stock. The punch is fastened to the upper die shoe by means of a retainer having a hardened backing plate. A slug can be seen falling through the lower die shoe. On the upstroke of the press, the stock is stripped from the punch by a simple fixed or tunnel stripper.

As the press and die close, the punch or punches first make contact with the stock. Exactly what occurs following the moment of initial contact of the punch on the stock varies based on:

1. The speed and mass of the press ram or slide.
2. The thickness and hardness of the stock.
3. The force required initiating yielding of the stock.

Initial Contact of Punch on Stock
Figure 1B illustrates a punch making initial contact with the stock. As the die closes, a compressive strain (2A) stores energy within the punch body. This is like compressing a spring.

Cutting operations are essentially a controlled process of plastic deformation or yielding of the material, leading to fracture. Both tensile and compressive strains are involved. Bending or distortion of the scrap metal trimmed away, slugs and in some cases, the part itself may occur.

Figure 2. Compressive strain (A) is developed in the punch as the die closes. Once the force developed by the closure of the press and transmitted through the punch (B) equals the yield point of the stock, plastic deformation (C) starts occurring. Smith & Associates
Simplified Sequence of Operations
As the press closes, the punch remains in contact with the stock until the force transmitted through the punch is great enough to exceed the shear strength of the material. The material continues to yield (3A) until complete fracture occurs. Next, the compressive strain in the punch releases and the slug pushed completely into the die opening (3B) at the bottom of the press stroke.

![Figure 3](image)

**Figure 3.** The stock continues to yield (A) until complete fracture occurs. Next, the slug is pushed into the die opening (B) at the bottom of the press stroke. *Smith & Associates*

Slug Discharge
Most slugs fall into the die opening by gravity as shown in (4A). If this does not occur, there are a number of means available to the die designer and diemaker to assure proper slug discharge. The final step is the withdrawal of the punch from the stock (4A) on the press upstroke. Figure (1A) shows tunnel or fixed stripper. Tunnel strippers have the advantage of simplicity and are adequate for many applications. However, spring loaded strippers are often required to provide precise stock control of the cutting process.

Roughness of Fracture
Plastic deformation of the material occurs throughout the cutting process. Cutting involves a controlled failure of the material. The fractured portion of the edge will be somewhat rough due to the tearing action that occurs. In thick materials, this roughness may be quite pronounced. Applying the term fracture to metal cutting operations is easily misunderstood. The fracture is seldom a sudden parting of the material. For example, when cutting low carbon steels such as SAE-AISI 1005 to 1008 the fracture is a plastic deformation of the material in which the stock is torn apart. Cutting also involves a controlled tensile failure of the material. The fractured portion of the edge will be somewhat rough due to the tearing action that occurs. In thick materials, this roughness may be quite pronounced.
How Die Clearance Affects Cutting Operations

Clearance Required for Various Operations
There are no absolute rules governing the amount of clearance between the punch and die. This clearance is normally expressed as a percentage of stock thickness per side. For mild steel, the clearance per side varies between five and twelve percent of stock thickness. In general, tight clearances will result in holes having a high ratio of shear or burnish to fracture and less taper at the expense of accelerated tooling wear.

Figure 5. Normal clearance (A) results in approximately one-third shear. Very large clearances (B) result in excessive die-roll, excessive burr height, and a large tapered fracture. Smith & Associates
Figure (5A) illustrates a sectional view of a punch, die, stock and fractured slug where normal clearance is being used. Normal clearance typically results in one-third burnish and two-thirds fracture.

Excessive clearance (5B) may result in die-roll at the point of punch entry and a large burr on the underside of the part. There is very little shear or burnish. The fracture is rough as well as having a large taper on the cut edge.

**Roughness of Fracture**

The fracture, which starts from each side, may not meet evenly. One or more sharp projections may result. Optimizing the amount of die clearance to best suit the material being cut, may require some experimentation to minimize an uneven fractured edge condition. By increasing clearance, within reasonable limits, cutting pressure is lowered, extending tool life. A limiting factor is the amount of taper permitted in the hole and the allowable burr height.

**The Effect of Insufficient Clearance**

Double breakage sometimes is observed when too little clearance is used. The fracture, which starts from each side, may not meet evenly. One or more sharp projections may result. Optimizing the amount of die clearance to best suit the material cut may be required to minimize an uneven fractured edge condition.

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**Figure 6.** Cutting (A) with insufficient clearance. As fracture continues (B), rough tearing occurs and the fracture paths will not meet. *Smith & Associates*

Figure (6A) and (6B) shows the progression of a fracture that does not meet due to insufficient clearance. Figure 7 shows the cut edge having double breakage.
Figure 7. Insufficient clearance (A) results in a double fracture or breakage condition. Appearance of a cut edge with a double breakage condition (B). Smith & Associates

Essential indicators for the diemaker to look for are secondary shiny areas on the inside of the hole and/or slug, check for a rough torn fracture. The fracture, which travels from both sides of the stock, may not be meeting evenly. This will leave a ragged edge. The die may burnish the torn peaks of the fracture.

The solution to double breakage problems usually requires increasing the punch to die clearance. Making the punch smaller is frequently the solution. This will maintain both the size of the hole and part. There will be an increase in the taper of the fracture.

Figure 8. Start of punch penetration and fracture (A) with a relatively large punch to die clearance. The fracture paths (B) will meet evenly. Smith & Associates

Effects of Increasing Punch to Die Clearance on Cut Edge Condition
Within reasonable limits, increasing the amount of clearance between the punch and die will decrease the required cutting force. Lowering the cutting force will usually increase the number of parts produced before the tool requires sharpening.
Clearances of 12 to 15 % per side may be required to eliminate double breakage problems in soft steels. The cut edges may have a pronounced taper in the fractured portion of the cut edge. Die roll and burr height may also be more pronounced. These edge conditions shown in Figure 9B may be acceptable for many applications.

If the clearance is very large, higher than normal forces may be required. The cut edges hole may have very pronounced die-roll, taper, and burr height. Very large clearances also result in high lateral forces on the punch and die that can shorten tool life.

![Figure 9. Completion of punch penetration and fracture (A) with a generous punch to die clearance. View of a cut edge (B) with large punch to die clearances. Smith & Associates](image)

**Factors Which Determine Cutting Forces**

The pressure required cutting through the stock increases with the ultimate tensile strength of the material. Die cutting requires less energy than parting metal by tensile failure. There is no absolute relationship between tensile strength and shear strength. Generally, shear strength is between 60 and 80 percent of ultimate tensile strength.

Generally, using the ultimate tensile strength of the material to calculate the cutting forces provides a substantial safety factor. For example, AISI-SAE 1010 cold-rolled steel has an approximate ultimate tensile strength of 56,000-psi (386 mPa) and shear strength of 42,000 psi (290 mPa).

The shear strength of the material increases due to the fast strain rates encountered in high-speed pressworking. The ultimate strength tensile strength used to calculate the required force provides a margin of safety.

**Case Study Example**

The importance of optimizing die clearance at The Western Electric Company is an important case study. The study was a high volume operation requiring many identical progressive dies punching thick silicon steel coil cores for telephone relays.
The hard abrasive nature of the material resulted in short runs even with excellent progressive dies design and construction. These punches and die sections for these tools used a combination of air hard and tungsten high-speed tool steels as well as cemented tungsten carbide.

The normal clearance for a new tool 5% per side with a $\frac{1}{4}^\circ$ die taper per side die taper. The die openings have a straight land of approximately 0.040-inch (1 mm) in order to increase die life.

Production requirements were very high. Several identical dies were in use at any time to meet production requirements. The tool was pulled and replaced with a sharp one avoiding part defects. In this way, a minimum amount of material needed to be ground away to sharpen the tool.

Careful inspection of the die edges conducted under high magnification with a toolmaker’s microscope measures the amount of die height to grind off. Enter the amount on the work order to sharpen the tool. New dies would typically produce 60,000 to 75,000 parts before pulling for sharpening.

**Western Electric Strategy to Maximize Tool Life**
The goal at Western Electric was to produce telephone relays having a life expectancy of several decades of trouble free service at the lowest possible cost. The die changeover routinely required well less than 10 minutes.

This fast changeover was a normal procedure several decades before the single minute exchange of dies occurred in Japan. Single minute of dies refers to changeover expressed in a single digit or under 10 minutes. This required maintaining constant shut height, providing positive die locators, and rapid die fastening changeover devices.

The key to minimizing die cost per part was to sharpen the tool before excessive burr height became a problem. Attempting to get several thousand more parts out of a dull tool usually would mean the difference between grinding 0.005-inch Vs 0.015-inch of tool steel away to obtain a sharp edge.

**Western Electric Case Study Tool Life Results**
Excessively tight clearances result in high cutting forces. Another effect is extreme pressure on the cutting edges, which shortens tool life. It was found that as the Western Electric relay dies developed greater clearance due to grinding into the $\frac{1}{4}^\circ$ per side die taper, the cutting forces decreased and the allowable runs became greater. As a set of die sections approached the end of their useful life, the clearance would be in excess of 8%. At this clearance, the allowable runs typically increased from 60,000 to 75,000 parts to over 130,000. When part dimensional tolerances and burr heights dictated rebuilding the die, runs were often as high as 150,000 pieces.
Determining Correct Clearances

There are no absolute rules governing correct die clearances. Generally, tight clearances in the 3% to 5% per side range result in:

1. Parts with less taper on the cut edge
2. Less tendency for the slug to be pulled from the die opening
3. Higher cutting forces
4. A tendency to have double breakage problems, especially in thick materials

As larger clearances in the 7% to 25% ranges are used, the result is often:

1. Longer punch and die life between resharpening
2. A need to use a means to insure against slug pulling
3. Lower cutting forces
4. Avoidance of double breakage
5. Greater edge taper and more burr height.

Calculation of Cutting Force Requirements

Generally, the ultimate tensile strength of the material used to calculate the cutting forces based on the area of material cut, provides a substantial safety factor. For example, AISI-SAE 1010 cold-rolled steel has an approximate ultimate tensile strength of 56,000-psi (386 mPa) and shear strength of 42,000 psi (290 mPa).

Rate of Deformation is a Factor
The shear strength of the material increases due to the fast strain rates encountered in high-speed pressworking. The ultimate strength provides a safety factor in such cases.

Determining Length of Cut
To calculate the force required cutting or shearing materials, the actual measurement of the total cut length is required. The dimensions on the part print provide a starting point. For progressive die work, all pilot holes and work done to cut the carrier strip must be included.
It is essential that the die designer or engineer calculate force requirements in order to determine the size and type of press required. An assumption that the pressroom can somehow fit a new job into an existing press can be a foolish blunder.

The length of cut, material thickness, and shear strength are calculation entry items. Some computer aided design (CAD) programs can automatically calculate tonnage.

**Determination of Theoretical Peak Cutting Force**

Multiply the total length of cut by the stock thickness in order to obtain the area of material cut. Finally, multiply the total area of cut by the shear strength of the material. Equation (1) is useful for calculating cutting forces. Making no allowance for shear angles or timing of entry provides a safety factor.

The same system of units is used. The formula is:

\[ F_s = L \times t \times S_s \]

**Equation (1)**

Where:

- \( L \) = Length of cut
- \( t \) = Thickness of material
- \( S_s \) = Shear strength of the material as defined by ASTM tests
- \( F_s \) = Force required to shear in the same system of units as \( L \), \( T \), and \( S \)

**Systems of Length, Area and Force Measurement**

In North America, many shops still carryout engineering calculations for stampings, using measurements based on the inch for length and thickness. Shear or yield strengths are based on pounds per square inch (psi). Usually, the press force in short tons, based on 2,000 pounds.

The metric system is in standard use throughout most of the world. Metric pressworking linear and area measurements are in terms of the meter, centimeter and millimeter. Pressworking forces in metric tons based on 1,000 kilograms are common in Asia. Most of the metric world uses the kilo-Newton (KN.) or mega-Newton (MN). The preferred metric unit for material strength is the kilo-Pascal (kPa) or mega-pascal (mPa).

**Calculation of Cutting Energy Requirements**

The energy required to cut through metal is often surprisingly small, especially when compared to processes such as sawing, oxy-fuel gas and laser cutting. This is because the actual shearing of the stock occurs when the punch or cutting steel penetrates the material approximately one-third stock thickness. An example of cutting energy requirements based on equation (2) follows.
*Using the foot-pound second (fps) system of units, the formula is:

\[ E = F \times D \]  \hspace{1cm} \text{Equation (2)}

Where:

\( E \) = Energy in foot pounds

\( F \) = Cutting force in pounds

\( D \) = Distance sheared in feet

Working in inch-tons may be more convenient. An inch ton equals 166.67 foot-pounds.

For example, adding a safety factor, the shear strength of mild steel is approximately 50,000 psi (345 mPa) or 25 short tons per square inch. Cutting a 12-inch (304.9 mm) diameter round blank 0.1875-inch (4.763 mm) thick requires the punch to penetrate only one-third material thickness or 0.0625-inch (1.588 mm), before fracture occurs.

The total area sheared is 7.0686 square inches, requiring a force of 176.72 tons. However, this force only acts through a distance of approximately 0.0625-inch. The required energy is 11.04 inch-tons or 1840.8 foot-pounds, which equals 2496 joules or watt-seconds. Operating the press at 60 strokes per minute (SPM) produces one blank per second. Ignoring frictional losses, a motor output of only 3.347 horsepower is required to restore energy to the flywheel.

**Effect of Cutting Speed on Force Requirements**

In high-speed pressworking, the force required might have measured values higher than expected based on the shear strength of the material. This is because as the punches shear the stock more rapidly, the strain rate of the material increases. In high-speed perforating operations, the measured cutting forces may approach the ultimate material strength.

**Side-Thrust or Lateral Forces**

Figure 10A illustrates the shear, tensile, and compressive forces that occur during the cutting process. The amount of lateral force varies with the cutting clearance and material.

For round and symmetrical holes, the lateral forces balance out. However, the die must be sufficiently strong to withstand high spreading forces. For notching, shearing and other unbalanced operations, the alignment system of the die must not allow excessive deflections to occur.
Figure 10. The shear, tensile, and compressive forces (A) that occur during the cutting process. As punch to die clearance increases, the lateral force or side thrust increases rapidly. The chart showing this (B) is based on equation (3). As side thrust increases, the cutting clearance may increase (C) leading to still greater side thrust or lateral forces and potential tool failure. Smith & Associates

Die Alignment System Requirements
This side-thrust or lateral force can result in excessive deflections of die components such as punches, heel blocks and guide pins. As lateral deflection occurs, clearances increase.

The lateral pressure can exceed the press force by a factor of three or more due to a wedge-like mechanical advantage. If not carefully controlled, the resulting misalignment can damage the tooling and produce scrap parts.

Effect of Die Clearance on Lateral Forces
The following equation gives an approximation of the side thrust or lateral force generated when cutting or shearing:
\[
\frac{C}{T - P} = \frac{F_H}{F_V}
\]

Equation (3)

Where \( T \) = material thickness

\( P \) = penetration, typically 0.33 times thickness \( T \)

\( C \) = clearance

\( F_V \) = cutting force

\( F_H \) = side thrust

Application of Formula (3) ¹

When applying equation (3) use adjustments for the type of material and die conditions. Figure 10A shows that cutting operations involve some bending. A chart, Figure 10B based on equation (3) shows this.

Excessive clearances and dull die steels can result in very large side thrusts. In extreme cases, the side thrust or lateral force may be so great that the die may shatter due to extreme pressures and interference of die components.

It is the function of the die alignment system such as guide pins and heel blocks to limit deflections due to side thrusts to acceptable values. Figure 10C illustrates how side thrust can cause punch deflection. The punch deflection increases the die clearance leading to still greater lateral forces.

NOTES: __________________________________________________________

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1 D. Smith, Die Design Handbook, Section 3, Die Engineering—Planning and Design, The Society of Manufacturing Engineers, Dearborn, Michigan, © 1990. Illustration 10A is courtesy of Tony Rante, P.E., who was Mechanical Engineering Manager for Danly Machine Company when the work was published.