Extrusion & Drawing

Comparison

Extrusion and drawing are metalworking processes that typically produce parts with a uniform cross section. The stuff that we’re extruding, drawing, or processing in some way is called the *workpiece*. In machining, the workpiece is what you cut. In grinding, the workpiece is what you grind.

In extrusion, you push the workpiece through a die. We’ve seen this already with plastics, but we can also do this with metals. In drawing, you pull the workpiece through a die. This is how food cans are formed, and how fine diameter wire is made from larger-diameter rods.

**Extrusion**

In *forward extrusion*, also called direct extrusion, the workpiece and the punch move in the same direction. You can produce either solid shapes or hollow shapes. This inside surface can be round, or square, or some other shape, depending on the shape of the mandrel.

With *backward extrusion*, also called indirect extrusion, the workpiece and the punch move in opposite directions. As the ram moves to the left, the extruding workpiece moves to the right.

You can combine forward and backward extrusion processes to create a *combination extrusion*, where the workpiece moves in both directions. The ram is removed, and an ejector pin pops the finished extrusion out of the die.

In *step extrusion*, we use two dies to vary the cross-section of the workpiece. This costs more money… you have to stop the press, change dies, then start up again. Or, use two presses, and move the workpiece from one press to the other. Why would you go to this trouble? Because it could be cheaper than machining, or other processes that involve cutting and scrap.

Any time you see the word *hydrostatic*, you know that pressure is involved. The field of hydrostatics is the study of forces on a body due to a pressurized liquid. Here, we’re using the ram to pressurize some oil, which drives the workpiece through the die. The ram never touches the workpiece. Hydrostatic extrusion is good for difficult-to-form metals, and the oil helps lubricate the die as the workpiece is deformed.
Closed-cavity extrusion is like die-casting with solid metal instead of liquid metal. We force the metal into the mold, then pop the mold apart. You can use lower-temperature mold materials than you can in casting, and you get the benefits of work hardening, grain flow, etc.

These cartoons show longitudinal cross sections, but not transverse cross sections, so we don’t know what shapes are being produced. They could be round, square, or something completely different: solid shapes, hollow shapes, channels, chalk trays for classroom chalkboards, etc.

Why do we extrude?

- **Scrap**: There is nearly no scrap because no material is being removed.
- **Microstructure**: Extruding work-hardens the workpiece, and produces grain flow along the axis of the part.
- **Dimensions**: Tolerances of ±0.001” are possible with extrusion.
- **Surface Finish**: There is no flash, no trim...the surface can be very smooth.
- **Tooling Cost**: Dies can run around $500.
- **High Volume**: Extrusion is cheaper than forging or machining for high-volume runs.

**Extrusion Ratio**

Let’s say we’re going to extrude some metal with a cross-sectional area \( A \) and a length \( L \). The initial cross-sectional area is \( A_o \), and the final cross-sectional area after extrusion is \( A_f \). We can define the extrusion ratio \( R \) as the ratio of the initial and final cross-sectional areas: 
\[
R = \frac{A_o}{A_f}.
\]

The reason that aluminum dominates the metal extrusion market is its extrusion ratio of 40. You can change the cross-sectional area of a piece of aluminum by a factor of 40. By comparison, the extrusion ratio of 1018 low-carbon steel is 5, and for Type 304 stainless steel it is only 3.5.

The volume of the metal doesn’t change when you extrude it. For a component with a uniform cross-section, 
\[
V = A_o L_o = A_f L_f,
\]
therefore 
\[
R = \frac{A_o L_o}{A_f L_f}.
\]
If the final area is one quarter of the initial area, then the final length will be four times the initial length.

**Cold Extrusion**

We can extrude at different temperatures. If the slug starts at room temperature, we call it *cold extrusion*. As the slug is extruded, its temperature rises. The metals that are easiest to cold extrude are at the top of the list...Al & Cu alloys. This is good for the wire industry. If it weren’t for the ability of Al and Cu to extrude easily, we probably couldn’t afford to produce and use as much electricity as we do today. As you go down the list, the metals get more difficult to extrude. Stainless wire is more expensive than Cu wire, partly because the raw material is more expensive, and partly because the processing is more expensive.

Cold extrusion work-hardens the metal, producing a stronger finished product with great surface finish.
Hot Extrusion

If the slug is preheated before extrusion, we call it hot extrusion. The table shows the temperature ranges used for various hot-extruded metals. Preheating costs money, but less pressure is required to extrude a hot, soft material than a cold, rigid material; therefore, much larger cross-sections can be extruded for a given sized press. However, the surface finish is not as good as with cold extrusion, and the finished part is not work-hardened.

In Europe, passenger railroad car manufacturers extrude aluminum panels 1 metre wide. The panels interlock to form the bottom, sides, top, etc. of a car...no need for welding, riveting, or adhesives, and assembly is much faster.

Wire Drawing

In extrusion processes, the workpiece is pushed through the tooling; in drawing processes, the workpiece is pulled through the tooling. We can draw discrete products out of sheet metal, like pop cans or soup cans, or we can draw continuous products, such as wire (< 3/8 in. diameter solid), rod (> 3/8 in. diameter solid), or tubing (hollow).

If we pull a rod between two undriven rollers, or if we pull a rod or wire through a die, then the diameter will be reduced, and the length will increase. Wire drawing requires multiple dies to reduce a large diameter to a smaller one. If the wire becomes too hard and brittle, it will need to be softened in an annealing furnace.

Stresses in Wire Drawing

It takes a force $F$ to pull wire through a die. The initial stress in the wire upstream of the die (to the left, before it enters the die) is $\sigma_o = \frac{F}{A_o}$. This stress must be greater than the yield strength of the wire, otherwise the wire cannot permanently deform as it passes through the die. The final stress in the wire downstream of the die (to the right, after it leaves the die) is $\sigma_f = \frac{F}{A_f}$. This stress must be less than the yield strength of the wire, otherwise the wire could neck and break downstream of the die.

Since $A_o > A_f$, $\frac{F}{A_o} < \frac{F}{A_f}$ which means $\sigma_o < \sigma_f$. How can this be, if $\sigma_o > \sigma_{YS}$ and $\sigma_f > \sigma_{YS}$? The only way wire-drawing can work is if the yield strength increases as the wire is drawn. As the wire deforms, it work-hardens, and its yield strength rises...so $\sigma_{YS_o} < \sigma_{YS_f}$. You cannot draw a metal that does not work-harden (such as lead). Only work-hardenable alloys can be drawn into wire.

<table>
<thead>
<tr>
<th>Hot extrusion alloys</th>
<th>Temperature (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead alloys</td>
<td>575</td>
</tr>
<tr>
<td>Aluminum alloys</td>
<td>575-1100</td>
</tr>
<tr>
<td>Magnesium alloys</td>
<td>575-1100</td>
</tr>
<tr>
<td>Zinc alloys</td>
<td>400-650</td>
</tr>
<tr>
<td>Copper alloys</td>
<td>1100-1825</td>
</tr>
<tr>
<td>Steels</td>
<td>1825-2375</td>
</tr>
</tbody>
</table>
Tubing

In the 1880s, the Mannesmann process was developed to pierce solid barstock. When radial forces are applied to a round bar, tensile stresses develop on the inside. If the stresses are high enough, the bar will split in the center. A mandrel helps the cavity to form a round cavity of a given diameter.

The bar is placed between two flat plates and crushed to enlarge the hole. Finally, the tube is run between two rollers (see diagram in textbook). The axes of the rollers are at a slight angle to the direction of the tube. A mandrel in the center of the tube helps form a smoother inside diameter.

Next, we want to draw the tube into a smaller OD, or a smaller wall thickness, or both. You can pull the tubing through a die, just like pulling rod or wire through a die.

You can pull the tubing through a die with a **stationary mandrel** (a.k.a. fixed plug) on the inside. The mandrel stays in the same position relative to the die, and the metal moves. The mandrel will form the ID, and the die will form the OD. You’ll get more control over the wall thickness this way.

You can use a **floating mandrel** (a.k.a. floating plug) on the inside. The floating mandrel is held in place by friction of the moving tubing. It stays in the same location with respect to the die, while the metal moves.

For short lengths, you can use a **moving mandrel**, that moves along with the tubing. You can only make tubing as long as the mandrel, so this method isn’t much use for long pieces of tubing. However, you can control the ID really well.

The result: **seamless tubing** with no welds, that’s been work-hardened by the drawing process. When we work-harden, the wire, rod, or tube gets stronger, harder, and more brittle.

You may need to **anneal** (soften) the workpiece between drawing stages. Otherwise, don’t anneal to produce very strong wire. High tensile fence wire has an ultimate tensile strength of 200 ksi. It takes 1500 lb. of tensile load to break. Advantage: if a tree falls on the fence, or a large animal runs into it, the wire stretches elastically, and recovers its shape when the load is removed. Compare with electric fence wire, which is much weaker…it will stretch plastically or break if a tree falls on the fence.
Drawing Wire Inside a Tube

Fort Wayne Metals manufactures pacemaker leads made of silver (which has better electrical conductivity than copper) encased in Carpenter MP35N alloy (for excellent corrosion resistance). MP35N is made of 20%Cr, 35%Ni, 10%Mo, and 25%Co. The graph shows the electrical resistance as a function of silver content for 0.006 inch diameter wire. The more silver we use, the less electrical resistance. Why do we worry about electrical resistance in a pacemaker lead? The lower the resistance, the longer the battery will last. Battery replacement involves surgery.

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