Frictionless Upsetting Let us assume that, by the application of some very good lubricant, we succeed in reducing friction to virtually zero. If we divide the cylinder into many small elements, each element now deforms equally; in other words, deformation is *homogeneous*. The cylinder becomes shorter and, to preserve constancy of volume [Eq. (4-2)], it assumes a larger diameter, but still remains a true cylinder (Fig. 9–4*a*). Because upsetting is a non-steady-state process, a complete analysis requires computation of variables at several points during the press stroke. In computations of a repetitive kind, it is best to follow a set sequence of operations, as shown here step by step. These steps, adapted to specific processes, will be followed in this chapter throughout.

Step 1: Find the volume of the part. In this case,

$$V = (d_0^2\pi/4)\,h_0 \tag{9-2a}$$

Step 2: In practice, only one of the final dimensions is defined. From constancy of volume, the final end-face area A_1 and diameter d_1 can be found

$$A_1 = A_0\frac{h_0}{h_1} = \frac{V}{h_1} \tag{9-2b}$$

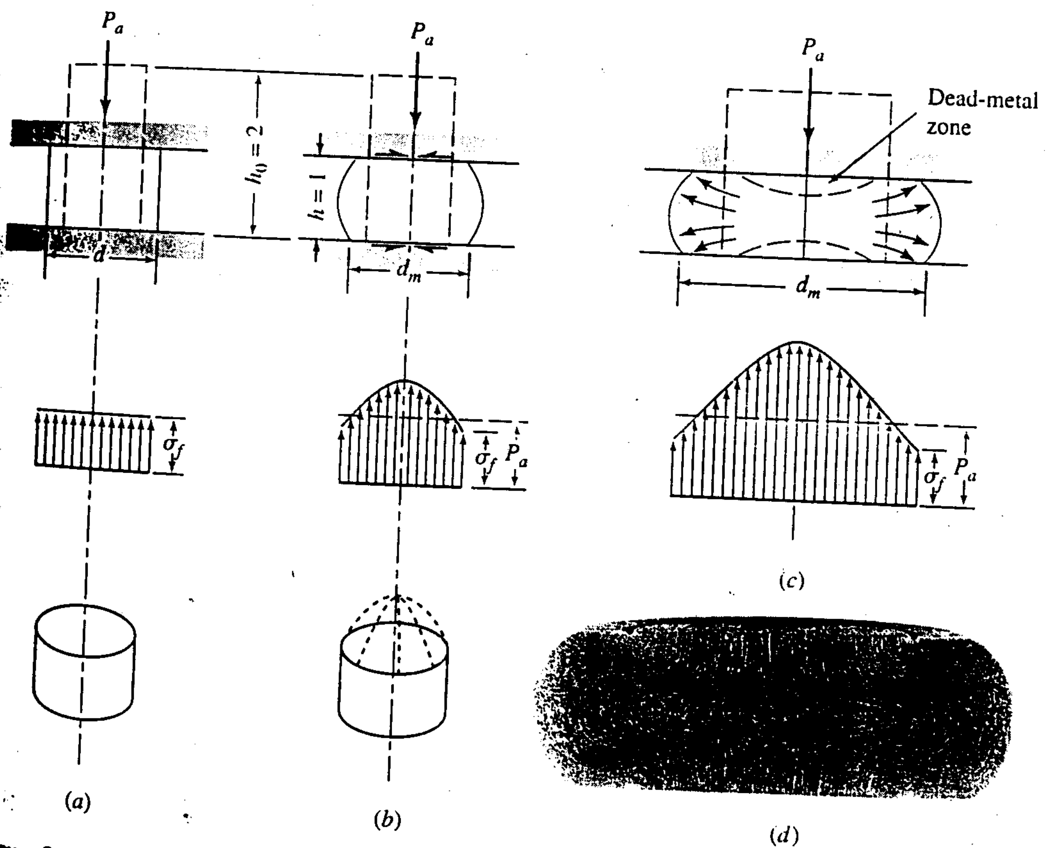


Figure 9–4 Interface pressures are (*a*) equal to the flow stress in frictionless compression but (*b*) friction generates a friction hill which (*c*) is larger for a large *d/h* ratio. (*d*) Sticking at the end face, caused by high friction or chilling, leads to folding over of the sides.

9

and

$$d_1 = \sqrt{\frac{4A_1}{\pi}} \tag{9-2c}$$

Step 3: The compressive engineering strain is needed only for conversational purposes. It is usually computed from the height change [Eq. (4-16)] but, because the volume remains constant, end-face areas can be used equally well:

$$e_c = \frac{A_1 - A_0}{A_1} = \frac{h_0 - h_1}{h_0} \tag{9-3}$$

Step 4: For purposes of computing the flow stress in cold working, true strain is

$$\varepsilon = \ln \frac{h_0}{h_1} \tag{8-5b}$$

Step 5: For hot working, the strain rate is also needed

$$\dot{\varepsilon} = \frac{v}{h} \tag{8-10}$$

Step 6: We are now ready to calculate the relevant flow stress. In cold working

$$\sigma_f = K\varepsilon^n \tag{8-4}$$

In hot working

$$\sigma_f = C\dot{\varepsilon}^m \tag{8-11}$$

(Note that strain rate must always be expressed in units of reciprocal seconds, s^{-1}.)

Step 7: To compute die pressure (also called *interface pressure*, p_a, where the subscript refers to axial symmetry), we need to check the effects of (*a*) stress state, (*b*) friction, and (*c*) inhomogeneity of deformation (Sec. 8-2).

a. The stress state is uniaxial, hence the flow stress is σ_f.

b. Since friction is absent, there is no increase in pressure.

c. The platen overlaps the workpiece, hence no indentation effect is possible and we need not worry about any h/L ratio.

Thus p_a is simply the uniaxial flow stress σ_f. This is the pressure that the tooling will have to withstand (Fig. 9–4*a*).

Step 8: The press force P_a is interface pressure multiplied by the *contact area* [Eq. (9-2b)]—the *area over which the pressure acts*). If we take the final point, where forces are highest, we find the size of press needed:

$$P_a = p_a A_1 \tag{9-4}$$

Step 9: For some forging equipment, it is necessary to know also the total energy expended in deforming the workpiece. This can be obtained by repeating the computations for the press force P_a at various points (progressively diminishing h) in the stroke. Thus, the force–displacement curve (Fig. 9–5) is defined. Force rises because the area A_1 increases rapidly. The area under the curve has

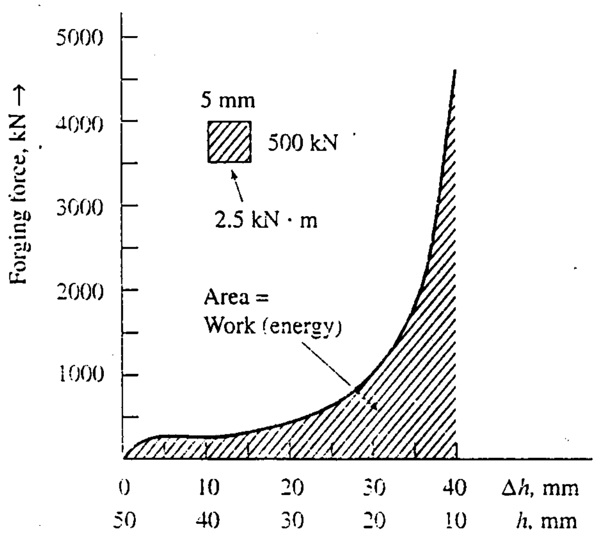


Figure 9–5 Upsetting forces rise steeply with progressing deformation; the area under the curve represents work.

the dimensions of work (work = force × distance). Thus, the work or energy E_a to be delivered by the press or hammer can be obtained by graphical or numerical integration of this area.

Step 10: The energy absorbed by the workpiece is converted into heat. In the absence of cooling, the adiabatic temperature rise ΔT is

$$\Delta T = \frac{E_a}{V \rho c} \tag{9-5}$$

where V is volume, ρ is density, and c is specific heat (more correctly, heat content per unit volume) of the workpiece. In practice, deformation takes place in finite time, and some of the heat is lost through conduction into the dies and by radiation and convection into the surrounding atmosphere. Therefore, the actual temperature rise is less but can, nevertheless, be significant. In hot working it may raise the temperature above the solidus to cause hot-shortness, and in cold working it may result in lubrication breakdown.

Upsetting with Sliding Friction In practice it is highly unlikely that zero friction can be attained even with the best lubricant (Table 8–4). Deformation of the cylinder requires that its end faces should slide on the tool surfaces, thus a measurable frictional shear stress τ_i is always present. This shear stress opposes the free expansion of the end faces, with two consequences (Fig. 9–4*b*):

1. The cylinder assumes a *barrel* shape. We may ignore this in calculating the new diameter (Step 2) simply by taking a mean diameter d_m from constancy of volume [Eq. (9-2[illegible])].

2. In order to overcome the frictional stress, a higher and higher normal pressure must be exerted as we move toward the center of the cylinder. At the free edge, the pressure equals σ_f and rises from here like a hill. With higher friction (from Sec. 8-2-3, expressed as a coefficient of friction μ or frictional shear factor m^*), the *friction hill* will be steeper. This is taken into account in Step 7*b*, in computing the average interface pressure p_a. A comparison of Fig. 9–4*b* and 9–4*c* shows that, for the same magnitude of friction, a cylinder of the same height but of larger diameter gives rise to a taller friction hill and, therefore, higher p_a. Thus, the d/h ratio or *shape factor*—which characterizes the squatness of the cylinder—determines, together with friction, the degree of pressure intensification. The average interface pressure p_a is then conveniently expressed as a multiple of the uniaxial flow stress σ_f. The *pressure-multiplying factor* Q_a (where the subscript signifies axial symmetry) must take into account the effects of both friction (μ or m^*) and workpiece geometry (d/h ratio). From theory, if m^* is used,

$$p_a = \sigma_f Q_a = \sigma_f \left(1 + \frac{m^*}{3\sqrt{3}} \frac{d_1}{h_1}\right) \qquad \text{(9-6)}$$

Alternatively, if μ is used, Q_a can be taken from Fig. 9–6 and

$$p_a = \sigma_f Q_a \qquad \text{(9-7)}$$

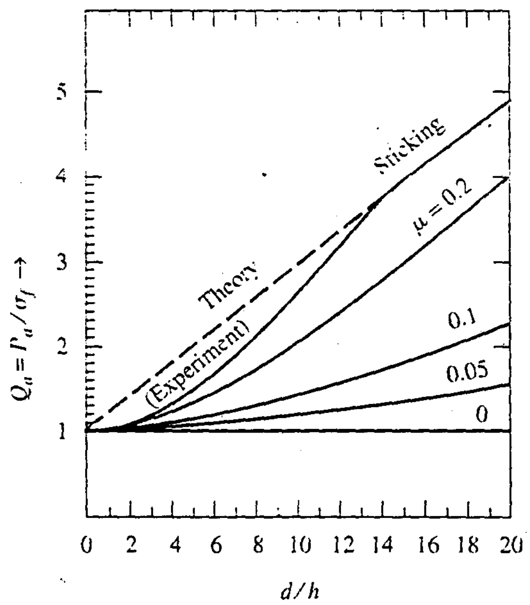


Figure 9–6 Average pressures in upsetting a cylinder increase with increasing friction and squatness of the cylinder. [*After J.A. Schey, T.R. Venner, and S.L. Takomana, J. Mech. Work. Tech.* **6**:*23–33 (1982). With permission of Elsevier Science Publishers.*]

The maximum stress $p_{a\ \max}$ is of importance for the die material. It is most simply computed with the use of m^*

$$p_{a\ \max} = \sigma_f \left(1 + \frac{m^*}{\sqrt{3}} \frac{d_1}{h_1}\right) \tag{9-8}$$

Upsetting with Sticking Friction In the extreme case, when the platen surface is rough and no lubricant is used, the interface shear stress τ_i may reach or exceed the shear flow stress τ_f of the workpiece material (Sec. 8-2-3) and movement of the end face is totally arrested. All deformation now takes place by internal shear in the cylinder; material adjacent to the platens does not move (*dead-metal zones form*) and the sides of the cylinder fold over (Fig. 9–4*d*). In nonisothermal forging, cooling of the end faces aggravates the situation, as shown by the flow lines in the specimen of Fig. 9–4*d*.

This is an unusual case of inhomogeneous deformation in that interface pressure becomes lower. Because the outer fibers of the cylinder are deformed by shearing superimposed on compression, the compressive stress needed is reduced (see Fig. 8–14*b*) and interface pressure remains low. The pressure-multiplying factor remains close to unity as long as $d/h < 2$. Simple theory cannot cope with this complexity and the limiting values of the pressure-multiplying factor given in Fig. 9–6 have been determined experimentally. Finite-element analysis gives similar results.

Example 9-2

An AISI 1045 steel billet of $d_0 = 50$ mm and $h_0 = 50$ mm is cold-upset to a height of $h_1 = 10$ mm, on a hydraulic press operating at $v = 80$ mm/s. The lubricant is mineral oil with EP additives. Compute the press force and energy expenditure.

Flow stress is from Table 8–2, friction from Table 8–4. To obtain the press force it would be sufficient to calculate for the final height only, however, the force is needed at several points of the press stroke if energy is to be determined too. It is best to set up a spreadsheet. The result is:

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Cold	1045 steel					d0 =	50 mm		h0 =	50 mm		V =	98 175	mm^3	
Flow stress			K =	950 MPa		n =	0.12								
Point	mu	v	h	d1	A1	ec	epsilon	eps dot	sigma f	d/h	Qa	pa	pa	Pa	Pa
No		mm/s	mm	mm	mm^2			1/s	N/mm^2			N/mm^2	kpsi	kN	tonf
				Eq. (9-2c)	Eq. (9-2b)	Eq. (9-3)	Eq. (8-5b)	Eq. (8-10)	Eq. (8-4)	Fig. 9-6	Eq. (9-7)			Eq. (9-4)	
0	0.1	80	50	50.0	1963	0	0	1.60	0	1	1.00	0	0	0	0
1	0.1	80	40	55.9	2454	0.20	0.223	2.00	794	1.4	1.10	873	127	2142	241
2	0.1	80	30	64.5	3272	0.40	0.511	2.67	876	2.2	1.25	1096	159	3585	403
3	0.1	80	20	79.1	4909	0.60	0.916	4.00	940	4.0	1.30	1222	177	5999	674
4	0.1	80	15	91.3	6545	0.70	1.204	5.33	971	6.1	1.40	1360	197	8901	1001
5	0.1	80	10	111.8	9817	0.80	1.609	8.00	1006	11.2	1.80	1810	263	17774	1998

Note the rapid rise in force as the height diminishes.

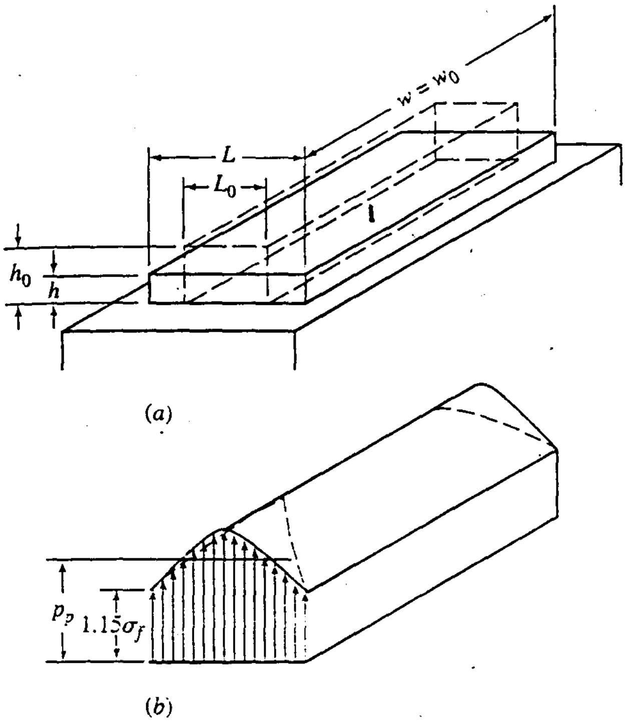


Figure 9–7 In upsetting a rectangular workpiece, (a) material flows in the direction of least resistance, marked L; (b) the friction hill now has a ridge shape.

tool surface; evidently, in upsetting with overhanging anvils, *the cross-sectional area remains constant while L increases as compression progresses* (Fig. 9–7a).

Since the two platens are parallel, material flows away from the centerline where no material flow takes place. The centerline is, therefore, called the *neutral line* (the line that divides the flow directions).

In the process of computation, Steps 1–6 are the same as in upsetting a cylinder. However, there are differences in Step 7:

a. First, the material begins to flow only on reaching the plane-strain flow stress $1.15\sigma_f$ (points 4 in Fig. 8–14b).

b. Second, the friction hill resembled a single-pole tent in axial upsetting (Fig. 9–4b) but it is now more like a mountain ridge (Fig. 9–7b). The cross section of the friction hill can still be computed by analogy to axial upsetting, as long as it is clearly understood that the friction hill is defined by that dimension of the workpiece which is measured *in the direction of major material flow*, i.e., the contact length L. Then, the friction hill will be higher for any given μ or m^* and for a larger shape factor (L/h ratio). The average pressure p_p (where the subscript refers to plane strain) is

$$p_p = 1.15\sigma_f\left(1 + \frac{m^*}{4}\frac{L}{h}\right) \qquad \textbf{(9-9)}$$

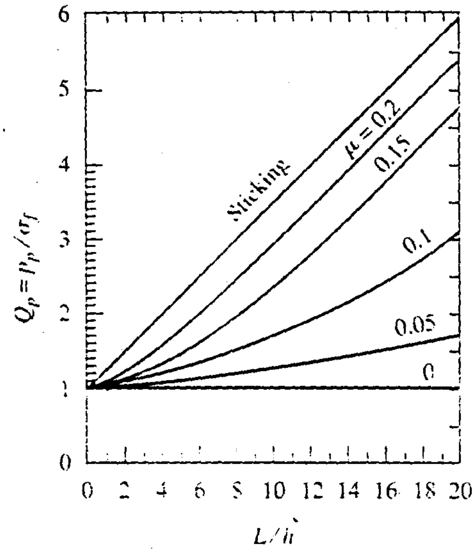


Figure 9–8 Average pressures in upsetting a rectangular slab increase with friction and L/h ratio. (*After J.F.W. Bishop, Quart. J. Mech. Appl. Math. 9:236–246 (1956). With permission of Pergamon Press.*)

When friction is expressed as μ, the pressure-multiplying factor Q_p is taken from Fig. 9–8 and the average pressure is

$$p_p = 1.15\sigma_f Q_p \tag{9-10}$$

By analogy to upsetting a cylinder [Eq. (9-8)], the peak of the friction hill will be

$$p_{p\ \max} = 1.15\sigma_f\left(1 + \frac{m^*}{2}\frac{L}{h}\right) \tag{9-11}$$

This peak develops at the neutral line.

In Step 8, the force P_p at any one point in the press or hammer stroke is again obtained by multiplying p_p by the *contact area* A_1 over which this pressure acts

$$P_p = p_p A_1 = p_p L w \tag{9-12}$$

Rectangular workpieces are frequently forged, and elements of more complex forgings can often be regarded as rectangular ones.

Example 9-4 **A** 302 stainless steel pin is to be produced from a square wire. One end is flattened, and the center is pinched. Compute the die pressure and force, assuming that no lubricant is used.

The flattening operation may be considered as upsetting a rectangular workpiece. Because of friction, the 100-mm length of the pin increases very little during flattening, and thi

Forging an Overhanging Workpiece A very different situation exists when the platen is narrow (and is usually called an *anvil*). Since the forged part now overhangs the anvil, we cannot expect the entire mass of the workpiece to be deformed, and deformation can become inhomogeneous even within the work zone. To judge the degree of inhomogeneity, we must return to Fig. 8–17. When the workpiece is wide, deformation is again in plane strain (Fig. 8–15*b*). *Major flow occurs in the direction of the short dimension of the anvil*, hence this now becomes L for purposes of analysis. Three distinct possibilities exist:

1. When $h/L > 8.7$ (Fig. 8–17*b*), the situation is the same as in indenting a semi-infinite body (Fig. 8–17*a*). It can be shown that the pressure required for indentation $p_{i\,max}$ is approximately 3 times the uniaxial flow stress σ_f of the material

$$p_{i\ max} = \sigma_f Q_{i\ max} = 3\sigma_f \tag{9-13}$$

Example 9-6 It will be recognized that while physically the situation shown in Fig. 8–17 appears very different from a hardness test (Fig. 4–12), the strain state is actually very similar. In hardness testing the specimen is, for all intents and purposes, infinite in the width, length, and thickness directions; thus, the indentor has to push the material out, as in Fig. 8–17*a*. Therefore, the *indentation hardness* of a material is approximately 3 times its uniaxial (compressive) flow strength. Since the highly localized deformation causes rather severe strain hardening, the indentation hardness is 3 times the mean flow stress σ_{fm} prevailing in the shear zones and, for reasons mentioned in Sec. 9-1-3, the TS is a good approximation of this mean value. It is for this reason that the indentation hardness is often taken as 3 × TS (remember that hardness is quoted in kg/mm^2). For a strain-hardening material, better agreement is obtained when hardness is taken as 3 times the flow stress at 7% cold work.

2. When $8.7 > h/L > 1$, the two deformation zones gradually interact, requiring less and less force to maintain plastic deformation (Fig. 8–17*b*). Therefore, the pressure-multiplying factor also diminishes, and can be taken from Fig. 9–9. The indentation pressure is

$$p_i = 1.15\sigma_f Q_i \tag{9-14}$$

It should be remembered that penetration of the two wedges sets up secondary tensile stresses which, at $h/L > 2$ can lead to internal fracture (*centerburst*) in a less-ductile material.

3. At a ratio of $h/L = 1$ the two deformation zones fully cooperate (Fig. 8–17*c*) and the material flows at a minimum pressure (at $1.15\sigma_f$).

4. When $h/L < 1$ (or, more conveniently, $L/h > 1$), friction becomes significant and the pressure-multiplying factor must be obtained according to Eq. (9-9) or (9-10). The friction hill is chopped on its sides and the pressure-multiplying factor drops when $w/L < 8$; it drops to Q_a when $w/L = 1$.

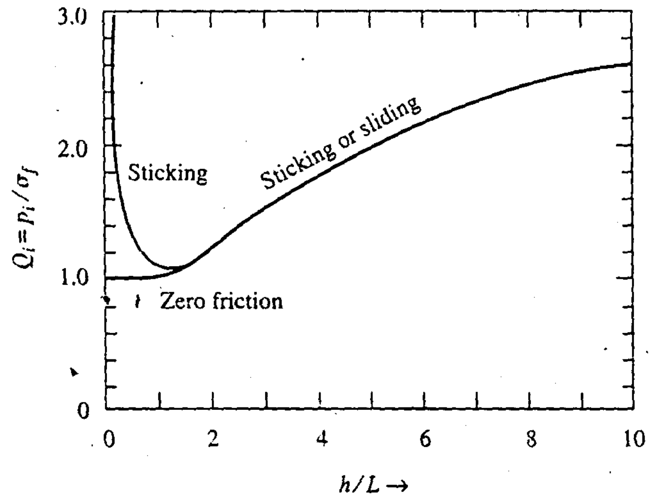


Figure 9–9 Pressures needed to indent a workpiece increase with h/L but are independent of friction. (*After R. Hill, The Mathematical Theory of Plasticity, Clarendon Press, Oxford, 1950. With permission.*).

Example 9-7

The pin in Example 9-4 is pinched at the center. Consider the geometry of the operation: the resemblance to Fig. 8–17*b* is obvious; $L = 2.5$ mm, $w = 6.35$ mm.

Step 4: $\varepsilon = \ln(6.25/5.2) = 0.2$.

Step 6: $\sigma_f = 1300(0.2)^{0.3} = 802$ N/mm^2.

Step 7c: $h/L = 5.2/2.5 = 2$, thus deformation is indeed inhomogeneous. From Fig. 9–9, $Q_i = 1.3$ for the end of stroke. Thus $p_i = (1.15)(802)(1.3) = 1200$ N/mm^2. Note that, because of the inhomogeneity of deformation, there is uncertainty about the proper value of strain and flow stress. However, the error is usually within practically permissible limits.

5. Inhomogeneous deformation is intentionally induced in *shot peening*. Many overlapping indentations are made with high-velocity shot, causing localized compressive deformation of the surface. Since the bulk of the workpiece is not affected, there are two possible consequences:

a. If all surfaces of the part are peened, balanced compressive residual stresses are set up and fatigue life is increased (Sec. 4-7, Fig. 4–18).

b. If only one surface is peened, unbalanced residual stresses cause curvature (Fig. 4–19). Well-controlled *peen forming* is suitable for correcting the shape of large containers and rocket-motor cases and for developing the shape of aircraft wing surfaces.

9-2-3 Open-Die Forging

In addition to upsetting and indentation, open-die forging employs various other processes, all of which can be analyzed by analogy to the processes discussed in hen friction is expressed as μ, the pressure-multiplying factor Q_p is taken from ig. 4-24 and the average pressure is

$$p_p = 1.15\sigma_f Q_p \tag{4-20}$$

In Step 6, the force P_p at any one point in the press or hammer stroke is again btained by multiplying p_p by the area A_1 over which this pressure acts

$$P_p = p_p A_1 = p_p L w \tag{4-21}$$

Rectangular workpieces are frequently forged, and elements of more complex orgings can often be regarded as rectangular ones.

Example 4-13

A 302 stainless steel pin is to be produced from a square wire. One end is flattened, and the center is pinched (as shown in the illustration). Calculate die pressures and forces, assuming that no lubricant is used.

The flattening operation may be considered as upsetting a rectangular workpiece. The 4-in length of the pin increases very little during flattening, and this dimension must be regarded as the width w during plane-strain compression (Fig. 4-23a). Most of the material gets displaced in the width of the pin; in terms of analysis, this becomes L.

Step 1: Since there is little change in the 4-in (width) dimension, $h_0 L_0 = h_1 L_1$ or $(0.25)(0.25) = (0.075) L_1$; thus $L_1 = 0.83$ in (the approximate value of 0.8 in marked in the illustration allows for some growth of the 4-in dimension).

Step 2: From Eq. (2-13a): $e_c = (0.25 - 0.075)/0.25 = 0.7$ (or 70%)

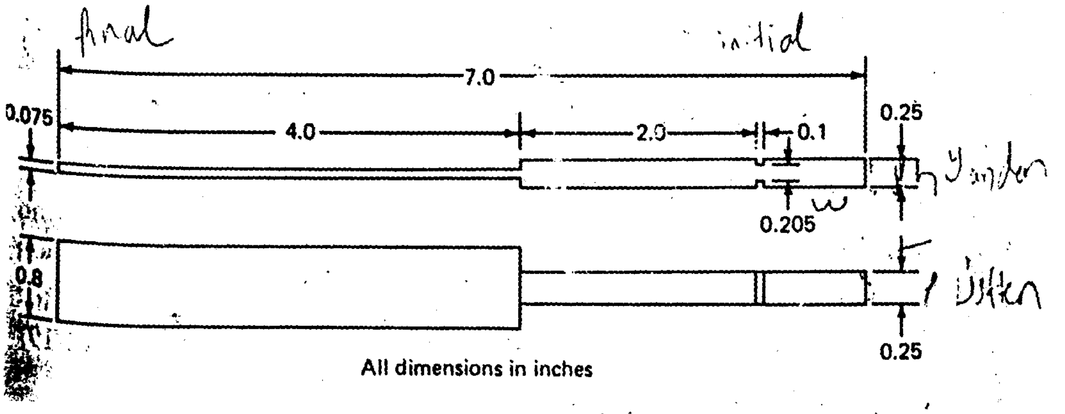
Step 3: From Eq. (4-5b): $\epsilon = \ln(0.25/0.075) = \ln 3.34 = 1.21$

For cold working, strain-rate sensitivity can be ignored.

Step 4: At the end of the stroke, the flow stress σ_f (from Table 4-2 after conversion): $\sigma_f = 190(1.21)^{0.3} = 200$ kpsi.

Step 5: From Fig. 4-24, for $L/h = 10.6$ and sticking friction, $Q_p = 3.7$ and, from Eq. (4-20), $p_p = 1.15(200)(3.7) = 850$ kpsi. This is too high for any tool material, and a suitable lubricant (Table 4-4) should be used. Assuming that the coefficient of friction is reduced to $\mu = 0.1$, from Fig. 4-11, $Q_p = 1.9$ and $p_p = 1.15(200)(1.9) = 437$ kpsi, which is still high but feasible (Sec. 4-6-1).

Step 6: The upsetting force, from Eq. (4-21): $P_p = 437(0.8)(4) = 1400$ klb or 700 tonf. Note the large size of press needed for this seemingly minor operation even with the application of a



All dimensions in inches

TABLE 4-2 MANUFACTURING PROPERTIES OF STEELS AND COPPER-BASED ALLOYS*
(Annealed condition)

		Hot-working					Cold-working						
			Flow stress,† MPa				Flow stress,‡ MPa						
Designation and composition, %	Liquidus/ solidus, °C	Usual temp., °C	at °C	C	m	Work-ability¶	K	n	$\sigma_{0.2}$, MPa	TS, MPa	Elongation, %	q R.A., %	Annealing temp.,§ °C
Steels:													
1008 (0.08C), sheet		< 1250	1000	100	0.1	A	600	0.25	180	320	40	70	850–900(F)
1015 (0.15C), bar		< 1250	800	150	0.1	A	620	0.18	300	450	35	70	850–900(F)
			1000	120	0.1								
			1200	50	0.17								
1045 (0.45C)		< 1150	800	180	0.07	A	950	0.12	410	700	22	45	790–870(F)
			1000	120	0.13								
~ 8620 (0.2C, 1Mn, 0.4Ni, 0.5Cr, 0.4Mo)			1000	120	0.1	A			350	620	30	60	
D2 tool steel (1.5C, 12Cr, 1Mo)		900–1080	1000	190	0.13	B	1300	0.3					880(F)
H13 tool steel (0.4C, 5Cr 1.5Mo, 1V)			1000	80	0.26	B							
302 SS (18Cr, 9Ni) (austenitic)	1420/1400	930–1200	1000	170	0.1	B	1300	0.3	250	600	55	65	1010–1120(Q)
410 SS (13Cr) (martensitic)	1530/1480	870–1150	1000	140	0.08	C	960	0.1	280	520	30	65	650–800
Copper-base alloys:													
Cu (99.94%)	1083/1065	750–950	600	130	0.06	A	450	0.33	70	220	50	78	375–650
				(48)	(0.17)								
			900	41	0.2								
Cartridge brass (30Zn)	955/915	725–850	600	100	0.24	A	500	0.41	100	310	65	75	425–750
			800	48	0.15								
Muntz metal (40Zn)	905/900	625–800	600	38	0.3	A	800	0.5	120	380	45	70	425–600
			800	20	0.24								
Leaded brass (1Pb, 39Zn)	900/855	625–800	600	58	0.14	A	800	0.33	130	340	50	55	425–600
			800	14	0.20								
Phosphor bronze (5Sn)	1050/950		700	160	0.35	C	720	0.46	150	340	57		480–675
Aluminum bronze (5Al)	1060/1050	815–870				A			170	400	65		425–750

*Compiled from various sources; most flow stress data from T. Altan and F. W. Boulger, *Trans. ASME, Ser. B, J. Eng. Ind.* **95**:1009 (1973).
†Hot-working flow stress is for a strain of $\epsilon \approx 0.5$. To convert to 1000 psi, divide calculated stresses by 7.
‡Cold-working flow stress is for moderate strain rates, around $\dot{\epsilon} \approx 1\ s^{-1}$. To convert to 1000 psi, divide stresses by 7.
§Furnace cooling is indicated by F, quenching by Q.
¶Relative ratings, with A the best, corresponding to absence of cracking in hot rolling and forging.

TABLE 4-3 MANUFACTURING PROPERTIES OF VARIOUS NONFERROUS ALLOYS[a]
(Annealed condition, except 6061-T6)

Designation and composition, %	Liquidus / solidus, °C	Hot-working: Usual temp., °C	Hot-working: Flow Stress,[b] MPa: at °C	Hot-working: Flow Stress,[b] MPa: C	Hot-working: Flow Stress,[b] MPa: m	Hot-working: Workability[f]	Cold-working: Flow stress,[c] MPa: K	Cold-working: Flow stress,[c] MPa: n	Cold-working: $\sigma_{0.2}$, MPa	Cold-working: TS,[d] MPa	Cold-working: Elongation,[d] %	Cold-working: q R.A., %	Annealing temp.,[e] °C
Light metals:													
1100 Al (99%)	657 / 643	250–550	300	60	0.08	A	140	0.25	35	90	35		340
			500	14	0.22								
Mn alloy (1Mn)	649 / 648	290–540	400	35	0.13	A			100	130	14		370
~ 2017 Al(3.5Cu, 0.5Mg, 0.5Mn)	635 / 510	260–480	400	90	0.12	B	380	0.15	100	180	20		415(F)
			500	36	0.12								
5052 Al(2.5Mg)	650 / 590	260–510	480	35	0.13	A	210	0.13	90	190	25		340
6061-O(1Mg, 0.6Si, 0.3Cu)	652 / 582	300–550	400	50	0.16	A	220	0.16	55	125	25	65	415(F)
			500	37	0.17								
6061-T6	NA[g]	NA	NA	NA	NA	NA	450	0.03	275	310	8	45	
~ 7075 Al(6Zn, 2Mg, 1Cu)	640 / 475	260–455	450	40	0.13	B	400	0.17	100	230	16		415
Low-melting metals:													
Sn (99.8%)	232	100–200				A				15	45	100	150
Pb (99.7%)	327	20–200	100	10	0.1	A				12	35	100	20–200
Zn (0.08% Pb)	417	120–275	75	260	0.1	A				130/170	65/50		100
			225	40	0.1								
High-temperature alloys:													
Ni (99.4Ni + Co)	1446 / 1435	650–1250				A			140	440	45	65	650–760
Hastelloy X (47Ni, 9Mo, 22Cr, 18Fe, 1.5Co, 0.6W)	1290	980–1200	1150	~ 140	0.2	C			360	770	42		1175
Ti (99%)	1660	750–1000	600	200	0.11	C			480	620	20		590–730
			900	38	0.25	A							
Ti-6Al-4V	1660 / 1600	790–1000	600	550	0.08	C			900	950	12		700–825
			900	140	0.4	A							
Zirconium	1852	600–1000	900	50	0.25	A			210	340	35		500–800
Uranium (99.8%)	1132	~ 700	700	110	0.1				190	380	4	10	

[a]Empty spaces indicate unavailability of data. Compiled from various sources; most flow stress data from T. Altan and F. W. Boulger, *Trans. ASME, Ser. B, J. Eng. Ind.* **95**:1009 (1973).
[b]Hot-working flow stress is for a strain of $\epsilon = 0.5$. To convert to 1000 psi, divide calculated stresses by 7.
[c]Cold-working flow stress is for moderate strain rates, around $\dot{\epsilon} = 1\ s^{-1}$. To convert to 1000 psi, divide stresses by 7.
[d]Where two values are given, the first is longitudinal, the second transverse.
[e]Furnace cooling is indicated by F.
[f]Relative ratings, with A the best, corresponding to absence of cracking in hot rolling and forging.
[g]NA Not applicable to the -T6 temper.

The maximum stress $p_{a\ \max}$ is of importance for the die material. It is most simply computed with the use of m^*

$$p_{a\ \max} = \sigma_f \left(1 + \frac{m^*}{\sqrt{3}}\frac{d_1}{h_1}\right) \tag{9-8}$$

Upsetting with Sticking Friction In the extreme case, when the platen surface is rough and no lubricant is used, the interface shear stress τ_i may reach or exceed the shear flow stress τ_f of the workpiece material (Sec. 8-2-3) and movement of the end face is totally arrested. All deformation now takes place by internal shear in the cylinder; material adjacent to the platens does not move (*dead-metal zones form*) and the sides of the cylinder fold over (Fig. 9–4*d*). In nonisothermal forging, cooling of the end faces aggravates the situation, as shown by the flow lines in the specimen of Fig. 9–4*d*.

This is an unusual case of inhomogeneous deformation in that interface pressure becomes lower. Because the outer fibers of the cylinder are deformed by shearing superimposed on compression, the compressive stress needed is reduced (see Fig. 8–14*b*) and interface pressure remains low. The pressure-multiplying factor remains close to unity as long as $d/h < 2$. Simple theory cannot cope with this complexity and the limiting values of the pressure-multiplying factor given in Fig. 9–6 have been determined experimentally. Finite-element analysis gives similar results.

Example 9-2

An AISI 1045 steel billet of $d_0 = 50$ mm and $h_0 = 50$ mm is cold-upset to a height of $h_1 = 10$ mm, on a hydraulic press operating at $v = 80$ mm/s. The lubricant is mineral oil with EP additives. Compute the press force and energy expenditure.

Flow stress is from Table 8–2, friction from Table 8–4. To obtain the press force it would be sufficient to calculate for the final height only, however, the force is needed at several points of the press stroke if energy is to be determined too. It is best to set up a spreadsheet. The result is:

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Cold	1045 steel					d0 =	50	mm	h0 =	50	mm	V =	98 175	mm^3	
Flow stress			K =	950	MPa	n =	0.12								
Point	mu	v	h	d1	A1	ec	epsilon	eps dot	sigma f	d/h	Qa	pa	pa	Pa	Pa
No		mm/s	mm	mm	mm^2			1/s	N/mm^2			N/mm^2	kpsi	kN	tonf
				Eq. (9-2c)	Eq. (9-2b)	Eq. (9-3)	Eq. (8-5b)	Eq. (8-10)	Eq. (8-4)		Fig. 9-6	Eq. (9-7)		Eq. (9-4)	
0	0.1	80	50	50.0	1963	0	0	1.60	0	1	1.00	0	0	0	0
1	0.1	80	40	55.9	2454	0.20	0.223	2.00	794	1.4	1.10	873	127	2142	241
2	0.1	80	30	64.5	3272	0.40	0.511	2.67	876	2.2	1.25	1096	159	3585	403
3	0.1	80	20	79.1	4909	0.60	0.916	4.00	940	4.0	1.30	1222	177	5999	674
4	0.1	80	15	91.3	6545	0.70	1.204	5.33	971	6.1	1.40	1360	197	8901	1001
5	0.1	80	10	111.8	9817	0.80	1.609	8.00	1006	11.2	1.80	1810	263	17774	1998

Note the rapid rise in force as the height diminishes.

Example 9-3 The billet of Example 9-2 is now hot-upset at 1000°C without a lubricant. Recompute the press force.

A	B	C	D	E	F	G	H	I	J	K	L	M	N
Hot	1045 st	T=	1000 C		d0=	50 mm		h0=	50 mm		V=	98 175 mm^3	
Flow	stress		C=	120 MPa		m=	0.13						
Point	mu	v	h	d1	A1	ec	eps	eps dot	sigma f	d/h	Qa	pa	Pa
No		mm/s	mm	mm	mm^2			1/s	N/mm^2			N/mm^2	kN
				Eq. (9-2c)	Eq. (9-2b)	Eq. (9-3)	Eq. (8-5b)	Eq. (8-10)	Eq. (8-11)		Fig. 9-6	Eq. (9-7)	Eq. (9-4)
0	st	80	50	50	1963	0	0	1.60	127.6	1	1.00	128	250
1	st	80	40	55.90	2454	0.2	0.223	2.00	131.3	1.40	1.10	144	355
2	st	80	30	64.55	3272	0.4	0.511	2.67	136.3	2.15	1.15	157	513
3	st	80	20	79.06	4909	0.6	0.916	4.00	143.7	3.95	1.40	201	988
4	st	80	15	91.29	6545	0.7	1.204	5.33	149.2	6.09	1.80	269	1757
5	st	80	10	111.80	9817	0.8	1.609	8.00	157.2	11.18	3.00	472	4631

Results are plotted in Fig. 9–5. Note the large drop in pressure and force relative to Example 9-2. To obtain the energy requirement, the area under the force–displacement curve is integrated. One square corresponds to (500 kN)(5 mm) = 2500 N·m; the total area is about 145 squares or 36 250 N·m (= 26 700 lb·ft or 320 000 lb·in).

Note that relative to cold forging, press force dropped by some 74%. Normally, a lubricant (with $\mu = 0.1$ from Table 8–4) would be used. Repeating the computation, press force would now be 2470 kN, i.e., one-seventh of the cold upsetting force.

9-2-2 Forging of Rectangular Workpieces

Two fundamentally distinct cases are to be distinguished: forging with *overhanging platens* and forging an *overhanging workpiece*.

Upsetting with Overhanging Platens When a rectangular slab is upset between two platens that are larger than the workpiece in all directions (Fig. 9–7a), the situation resembles that of the axial upsetting of a cylinder, at least as far as deformation in the *narrower* cross section is concerned. Overall, however, the situation is different, especially if one of the dimensions of the slab is much greater. *The material will always flow in the direction of least resistance.* Frictional resistance is proportional to the distance over which sliding takes place. Therefore, flow in the longer direction (which we shall call, for purposes of analysis, the *width* direction w), is much restricted and the condition of plane strain (Fig. 8–15a) is approximated. *Most material flow takes place in the short direction*, and for purposes of analysis we shall call this the *contact length* L between workpiece and