'METAL-CUTTING' ENERGY ABSORBERS

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ABSORBING kinetic energy by cutting or "skinning" metal produces a highly predictable deceleration rate. Decelerators based on this principle are simple and inexpensive because they convert all kinetic energy into nonrecoverable work and need no recovery system.

Metal cutting dissipates energy in two ways: plastic shear deformation of the metal chips and friction of the chips against the cutting tool. Shear and frictional energies are characterized by a single parameter called the specific energy of cutting U. This parameter is a measure of the energy required to form a certain volume of chips and is weakly related to the cutting speed and depth of cut. It is approximately 100,000 in.-lb/in.^{3} for aluminum and 300,000 in.-lb/in.^{3} for steel.

A typical metal-cutting energy absorber consists of a long cylindrical rod drawn through a circular cutting tool with a smaller diameter. To avoid buckling, the rod is pulled rather than pushed through the tool. Because long life is not required, tools can be made of low or medium carbon steel.

To design a metal cutting energy absorber, first determine the weight to be stopped W, the velocity V, the maximum allowable deceleration rate a_{max}, and the maximum available stopping distance l_s. Rod material is chosen based on its specific cutting energy and yield strength, and the number of rods is chosen so that retarding force is appled symmetrically. A safety factor of at least 2.0 must be imposed so the system can withstand the initial impact force.

Stopping distance, or length of cut, l_{st} is constrained both by the maximum space available and by the maximum allowable deceleration (which is specified to prevent damage to the device being stopped or to its contents). Thus, minimum stopping distance l_a is

$$l_a = V^2/2a_{max}$$

and $l_a < l_{st} < l_s$.

Once stopping distance is known, the actual deceleration rate can be computed from

$$a = V^2/2l_{st}$$

Then, retarding force is calculated from

$$P_r = Wa/gN$$

Working stress in the rod is $\sigma_w = \sigma_y/f_s$, and cut diameter of the rod is

$$D' = (4P_r/\pi\sigma_w)^{1/2}$$

Actual rod diameter D is chosen from standard mill stock as the next larger size from D'.

Radial depth of the cut is

$$t = P_r/\pi UD$$

and ID of the cutting tool is

$$D_i = D - 2t$$

If D_i is smaller than D', then a larger rod must be used to provide the strength required. If D_i is larger than D', then the rod size is adequate.

Variations in rod or cutting tool sizes, ΔD and ΔD_i, cause variations in retarding force, deceleration rate, and stopping distance. These variations are

$$\Delta P_r = (\pi/2)UD(\Delta D + \Delta D_i)$$

$$\Delta a = \Delta P_r Ng/W$$

$$l_{max} = V^2/2(a - \Delta a)$$

$$l_{min} = V^2/2(a + \Delta a)$$

If the maximum stopping distance exceeds the maximum available space, then either tighter tolerances should be specified on the cutting tool, or the deceleration-dependent stopping distance should be shortened.

For example, consider a rapid transit car weighing 23,000 lb and traveling at 25 fps. If deceleration rate is limited to 1g (32.2 ft/sec^2), design an emergency stopping system that will stop the car within 20 ft.

To provide symmetrical load application, four rods of 6061-T6 aluminum alloy are used. U is 100,000 in.-lb/in.^{3} and yield strength is $\sigma_y = 40{,}000$ psi. A safety factor of 6.0 is arbitrarily applied because of the application.

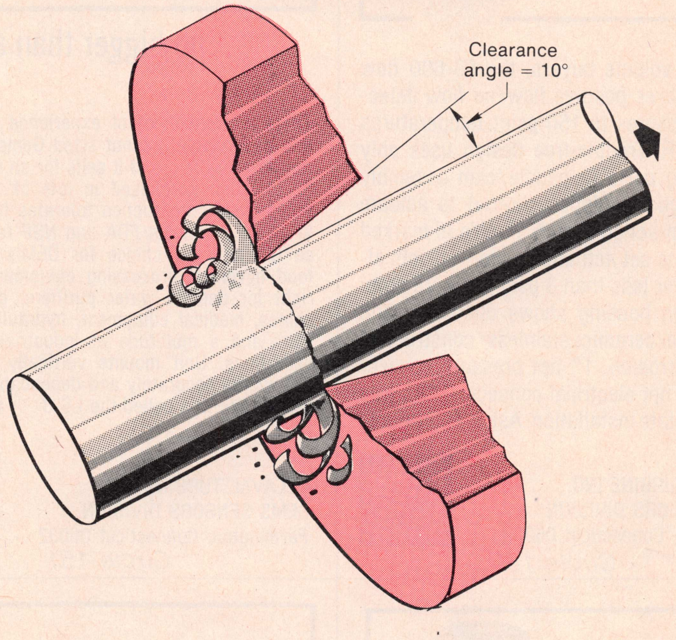
The first step is to determine the stopping distance. Deceleration-limited stopping distance is $l_a = (25^2)/2(32.2) = 9.7$ ft. Thus, an "average" stopping distance of 14.5 ft will be used in the calculations. Deceleration rate over this distance is $a = (25^2)/2(14.5) = 21.6$ ft/sec², and retarding force is $P_r = (23{,}000)(21.6)/(32.2)(4) = 3{,}860$ lb.

Working stress in the rod is $\sigma_w = 40{,}000/6 = 6{,}667$ psi, and cut diameter of the rod is $D' = [4(3{,}860)/\pi(6{,}667)]^{1/2} = 0.859$ in. The next larger standard rod size is 0.875 in. Therefore, depth of cut and tool ID are $t = 3{,}860/\pi(100{,}000)(0.875) = 0.0140$ in. and $D_i = 0.875 - 2(0.0140) = 0.847$ in. Because $D_i < D'$, a rod with a 1.00-in. diameter must be used. Rechecking gives $t = 0.0123$ in. and $D_i = 0.9754$ in., which meets the requirement that $D_i > D'$.

The rods are manufactured with a tolerance of ±0.002 in., and tool ID tolerance is also ±0.002 in. Therefore, variations in retarding force and deceleration rate are $\Delta P_r = (\pi/2)(100{,}000)(1.00)(0.004) = \pm 628$ lb and $\Delta a = 628(4)32.2/(23{,}000) = \pm 3.5$ ft/sec². Maximum stopping distance based on worst case tolerances is $l_{max} = (25^2)/2(21.6 - 3.5) = 17.3$ ft.

Because l_{max} leaves only 2.7 ft of extra stopping distance, cutting tool tolerance is tightened to ±0.0005 in., and the new worst-case stopping distance is $l_{max} = 16.1$ ft. Thus, four 20-ft long, 1.00-in. diameter rods will safely stop the car if a 0.9754-in. ±0.0005-in. ID cutting tool is used. MD

Metal-Skinning Energy Absorber



Decelerator absorbs vehicle kinetic energy by skinning off the outside diameter of a cylindrical rod. Energy is converted to plastic shear deformation of the chips and friction of the chips against the cutting tool. No residual energy remains in the system.

Nomenclature

a = Deceleration rate
a_{max} = Maximum deceleration rate
D = Rod diameter
D_i = Tool ID
D' = Cut diameter
f_s = Safety factor
g = Gravitational constant
l_a = Deceleration-limited stopping distance
l_{max} = Worst-case stopping distance
l_{min} = Minimum stopping distance
l_s = Maximum available stopping space
l_{st} = Stopping distance
N = Number of rods
P_r = Retarding force
t = Cutting depth
U = Specific energy of cutting
V = Vehicle speed
W = Vehicle weight
σ_w = Working stress
σ_y = Yield stress