Stuart Keeler (Keeler Technologies LLC) is best known worldwide for his discovery of forming limit diagrams, development of circle grid analysis and implementation of other press shop analysis tools. Stuart's sheetmetal forming experience includes 24 years at National Steel Corporation and 12 years at The Budd Company Technical Center, enabling him to bring a very diverse background to this column and the many seminars he teaches for PMA.

Keeler Technologies LLC
P.O. Box 283
Grosse Ile, MI 48138
Fax: 734/671-2271
E-mail: keeltech@comcast.net

Stuart Keeler's next seminars are "Amateur Metallurgy for the Professional Stamper," scheduled for May 23 in Greenville, SC, and a brand-new seminar, "Circle Grid Analysis and Forming Limit Diagrams," scheduled for June 22 in Chicago, IL. Check www.metalforming.com for these and other seminars.

THE SCIENCE OF FORMING | STUART KEELER

Troubleshooting Cup Drawing

Deep-drawn cups come in all sizes—from tiny cups the diameter of a pencil lead to tanks for welding gases made from 0.25-in.-thick blanks that are 4 ft. in diameter. In spite of these large dimensional differences, all deep-drawn cups follow the same forming mode and are constrained by the same limits. While these deep-drawn cups look complex, troubleshooting is straightforward.

A press shop is trying out a newly constructed set of dies. All of the cups are splitting at one third of the design depth. Management panics. How can the die ever be changed to increase drawn cup depth by a factor of three? To answer this question one must dig deeper into how and why forces develop in cup drawing.

Fig. 1 shows the two primary forces in cup drawing. The first (F_F), the total flange force, is the total of all the forces resisting the movement of material from a circular blank into a cylindrical cup. To overcome this resistance, the punch must generate and transmit through the cup wall a force F_P greater than F_F without causing the material to thin and tear. For flat-bottom cups one can ignore what occurs at the base of the cup and simply look at the force transmitted through the cup wall.

To further examine the required total flange force, F_F must be plotted as a function of punch stroke (Fig. 2). The most obvious feature of Fig. 2 is that total flange force occurs at approximately one third of the punch stroke. This happens because the flange volume in the blank decreases from maximum to zero with the punch stroke. However, the stress increase due to work hardening does not increase linearly, but as a parabolic function. The product of the two represents the deformation force that peaks at about one-third of the punch stroke.

The apparent disaster encountered by the press shop described above really is a case of going just over the edge of the deformation cliff. Once past the one-third point of the punch stroke, the total flange force begins to decrease. Small process adjustments should be able to ensure successful deep-drawn parts.

Deep drawing higher-strength steels means the stress curve shown in Fig. 2 will be flatter. Thus, the peak force will be experienced earlier than one-third through the stroke.

The deformation force in Fig. 2 describes the force required to generate the final form. Unfortunately, two additional forces must be added to the deformation curve to obtain the total flange force (F_F). These forces are part of the

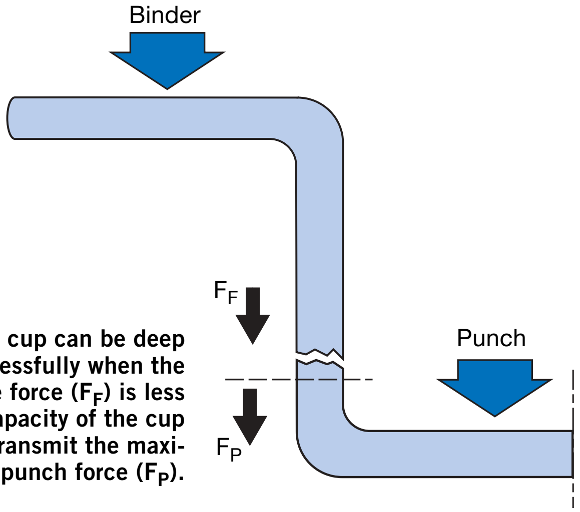

Fig. 1—A cup can be deep drawn successfully when the total flange force (F_F) is less than the capacity of the cup wall to transmit the maximum punch force (F_P).

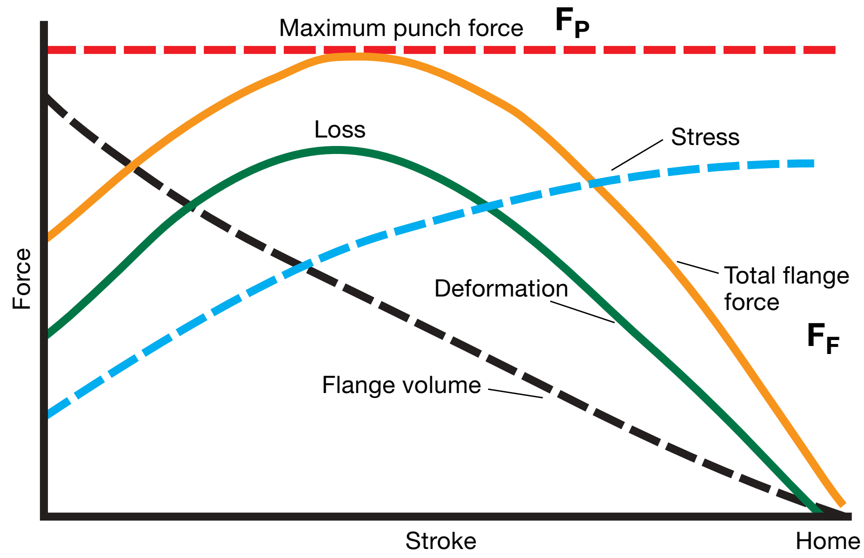

Fig. 2—The total flange force (F_F) is the sum of the basic deformation force to generate the cylindrical cup plus the loss forces (frictional forces plus bending and unbending over the die radius).

forming mode, but are considered as a loss because they do not contribute to the final geometry of the cup.

The first loss force is friction. The amount of frictional force to overcome depends on the surface topography of the sheetmetal and tool, the capability of the lubricant between the two work surfaces, blankholder force, interface temperature and other factors. Obviously, lower friction conditions will decrease the total loss force and therefore reduce the peak force.

The second loss force is the bending and unbending over the die radius. If the entire blank is pulled into the cup wall, then the die radius is not a specification of the cup design. If a flange remains on the cup, the specified die radius becomes a major factor in determining whether the total flange force will be under the maximum punch force. Bending and unbending the sheetmetal over a die radius less than four times the sheet thickness will exponentially drive up the loss force and cause wall breakage.

Some cup-drawing operations actually fail during the initial 10 percent of punch stroke. According to Fig. 2, the total flange force should be well below the maximum punch force. The forming of the drawn cup actually is accomplished in two stages. The first stage is an embossment, where the bottom of the cup is stretched into the blank. When the embossment force becomes large enough, the blank begins its inward travel to create most of the cup wall. If the initial restraint is too large (blank size, friction and die radius bending), the blank does not move and the punch tears through the embossment. This is easily detected by measuring the initial and remaining blank to verify no blank movement.

In terms of allowable blank size, the limiting draw ratio (LDR) specifies the maximum blank size that can be drawn into a specific die opening (or punch size). For cold-rolled AKDQ steel this ratio is approximately 2.2. For cold-rolled vacuum-degassed, interstitial-free steel the LDR increases to approximately 2.4. For all hot-rolled steels and higher-strength cold-rolled steels the LDR is 2.0. For aluminum, brass and other nonferrous metals, the number is approximately 1.8. A conservative safety margin is used to bring the actual draw ratio well below the LDR. Compensation for the reduced draw ratio is achieved by one or more redraw operations, which either reduce the cup diameter or increase the cup height (larger blank) to attain part-print dimensions.

Failure at the end of the stroke, when the total flange force should be almost zero, usually is due to insufficient clearance between punch and die. The blank edge is in uniaxial compression and can increase in thickness by 45 percent. If clearance is not allowed for this thickening, the blank locks upon entry into the die opening while the punch continues its stroke and rips out the bottom of the cup.

Cup drawing may look complex but the troubleshooting procedures are logical, once the generation of the forming forces is understood. **MF**