Recent Developments in Profiled-Edge Lamination Dies for Sheet Metal Forming

Daniel F. Walczyk[1], David E. Hardt[2]

Introduction:

The Profiled-Edge Lamination (PEL) method was developed by the Walczyk and Hardt [1] as an improvement over the current method of stacking and bonding contoured laminations in terms of the lead-time and cost of tooling development for sheet metal forming dies. It is also a viable alternative to conventional CNC-machining of such dies. In pursuit of successful commercial realization of the PEL method in industry, this paper discusses several important issues including:

- the origin of this method and advantages over other tooling techniques
- the general procedure for creating PEL machining instructions
- determining the geometric error introduced by the straight bevel approximation
- the propensity for PEL die delamination from high forming loads
- methods for cutting bevels into die laminations and
- the machinery needed for PEL die fabrication.

Future research and developmental work on the PEL die method will also be outlined.

I. Background on the PEL Die Method:

Using a laminated construction for sheet metal forming dies is a relatively new idea. Kunieda and Nakagawa successfully created a sheet metal forming die made of horizontally-oriented laminations by slicing up a CAD model of the 3-D forming surface and using the resulting data to CNC laser-cut the required contours out of sheet material [2]. The contoured laminations were secured to one another by a combination of cementing with adhesives, clamping with bolts, and laser-welding the edges. Nakagawa et al. formed a solid tool out of stacked laminations by diffusion-bonding the laser-cut laminations together [3]. Since the lamination edges were cut normal to the surface and not beveled, the forming surface of the resulting dies had a stepped profile and thus needed to be CNC-machined with finishing cuts, ground, and polished in order to achieve the necessary smoothness. Some industries completely avoid this secondary smoothing operation used to remove the stepped profile by filling in the steps with epoxy or some other tough material [4].

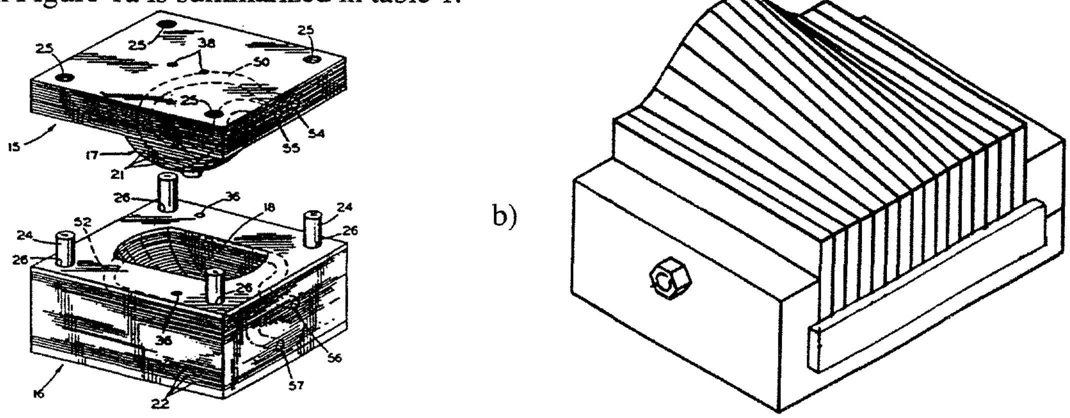
Weaver was granted a patent for a laminated tooling with the contours machined into each lamination using beveled edges and not just normal cuts [5]. This change in the art obviates a smoothing operation and only requires a grinding and polishing operation as shown in Figure 1a. The smoothing operation also becomes unnecessary as the laminations get very thin and the resulting steps between laminations are negligible. For instance, LOM can create a forming die for low force forming that has nearly smooth surfaces since laminations are as thin as 0.05 mm. The biggest limitation with current LOM paper/adhesive models is that they have low compressive strength (26 MPa). This is one-fifth the compressive strength of the cast epoxy (140 MPa) that is used in forming dies. Other materials (e.g. ceramic & metal tape) for LOM models are currently being developed that may take higher compressive loads.

As previously mentioned, Walczyk and Hardt recently introduced the PEL method of constructing sheet metal forming dies [1]. As seen in Figure 1b, a PEL die generally comprises a

[1] Assistant Professor, Department of Mechanical Engineering, Aeronautical Engineering & Mechanics, Rensselaer Polytechnic Institute, Troy, NY.
[2] Professor, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA.

plurality of die lamination members, each die lamination member being substantially planar and each being disposed in a vertical plane and stacked together side-by-side in an array. The top edge of each die lamination is simultaneously profiled and beveled in such a way as to approximate a segment of the intended die surface. Specifically, this top edge is continuous in the y-direction and approximated in the x-direction. The die lamination members may be held together in a stacked array by any suitable means, but preferably with a clamping frame as shown in Figure 1b. A common registration corner and the bottom edge of each lamination allows for easy and uniform registration in the clamping frame. One or more holes uniformly positioned in the sides of each lamination allows the whole array to be clamped so that no adhesive or other means of holding the array of die lamination members together is required. If the shape of the forming surface has to be change during the die development, the die laminations can easily be separated for re-machining to update the die shape. The PEL die can be made into a solid die apart from this process by suitable means (e.g. diffusion bonding) if needed or desired. Generally at least a portion of the die lamination members have a continuously changing beveled top edge. When placed together in a vertical stacked array, the top edges of the die lamination members, in the aggregate, form the top surface of the die. The advantages that a PEL array construction has over the contoured lamination stack shown in Figure 1a is summarized in table 1.

a)



b)

Figure 1 - a) Stack of contoured, beveled laminations (Weaver Die) and b) an array of Profiled-Edge Laminations.

Table 1 - Comparison of laminated die constructions

Stack of Contoured Laminations	Array of Profiled-Edge Laminations
Difficult to automate the handling of laminations during cutting.	Laminations can slide past the profiled-edge cutting means since only top edge is cut.
Difficult to register laminations during die assembly.	Laminations are easily registered with a base plate and an edge guide.
Difficult to secure lamination stack into a rigid tool.	Lamination only needs to be clamped from the side.
Typically, laminations need to be permanently secured. Reshaping of die surface requires CNC-machining.	Unclamped laminations can be individually recut to new die shape.

II. Creating PEL Machining Instructions from a CAD Model:

The first step in the process of creating a PEL die consists of creating a 3-dimensional model of the die's forming surface. The surface model may be created by a die designer using CAD software; or by a locus of surface coordinates defined by an iteration of a closed-loop control algorithm, an FEA model of the die, or a reverse engineering scan from a coordinate measuring machine. The details of extracting the PEL machining instructions from a surface model of a die are beyond the scope of this paper. However, to illustrate the data manipulation process required, the general procedure of using a CAD surface model for this purpose will be discussed.

The intersection of a 3-dimensional CAD surface model and a Y-Z cutting plane situated on the X-axis at a certain point is a 2-dimensional curve. Furthermore, if the Y-Z plane is repositioned along the X-axis by constant increments such as 1 mm, the collection of curves produced by each of the same plane/surface intersections will approximate the shape of the original 3-D surface. The algorithms developed by Phillips et al. and Bobrow for determining the intersection of two arbitrary surfaces (analytic or parametric) can be used [6,7]. The true 3-D surface between two adjacent curves can be approximated by connecting them with a bevel. This connecting bevel constitutes the profiled-edge of each PEL die lamination. The reader will note that the approximation of the 3-D surface gets better as the curves get closer together, i.e. as the x-increment decreases. This collection of curves serves as the machining database for creating a PEL die with the desired forming surface.

Any one of several cutting methods (e.g. laser cutting, machining with an endmill, abrasive waterjet cutting, plasma-arc cutting) can be used to create the bevels into the top edges of the die laminations. These methods will be discussed in more detail in a later section. With whatever method is used, the data needed for cutting the compound bevels is the position point $\mathbf{P_1}$ on the nearside of the lamination with coordinates $(\mathbf{x_1},\mathbf{y_1},\mathbf{z_1})$ and a unit directional vector $\vec{V} = V_1 \cdot i + V_2 \cdot j + V_3 \cdot k$ or just written as $(\mathbf{V_1},\mathbf{V_2},\mathbf{V_3})$. As shown in Figure 2a, the vector components of $\vec{V}$ defined by P_1 and $\mathbf{P_2}$ (coordinates x_2,y_2,z_2) are

$$V_1 = \frac{x_2 - x_1}{|\vec{V}|} = \frac{t_L}{|\vec{V}|}, \quad V_2 = \frac{y_2 - y_1}{|\vec{V}|}, \quad \text{and} \quad V_3 = \frac{z_2 - z_1}{|\vec{V}|}. \qquad (1)$$

where:

$$|\vec{V}| = \left[t_L^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2\right]^{\frac{1}{2}}.$$

Point P_1 is easy to determine because x_1 and y_1 will be prescribed and z_1 is explicitly defined by the nearside intersection curve (see Figure 2a). Point P_2 is harder to define since there is no particular one associated with the defined point P_1. To determine P_2, an iterative procedure which minimizes the geometric error introduced by the straight bevel approximation is required. When P_2 is determined then the bevel cutting head will only require translation along the Y and Z-axes, i.e. x_p is kept constant, and rotation about the two orthogonal axes.

There are many forming dies used in industry for such processes as stretch forming and rubber forming that only have mild curvatures and low draws. For these types of die shapes, reasonable die shape fidelity, i.e. small deviations of the machined shape from the desired CAD shape, can be achieved even if the bevel cutting head is only allowed to rotate about the Y-axis. This will allow for simple planar beveling but not compound 3-D beveling like that shown in Figure 2. The position point P_1 and orientation vector $\vec{V}$ of the bevel cutting head are defined by (x_1,y_1,z_1) are coordinates $(0,V_2,V_3)$, respectively.

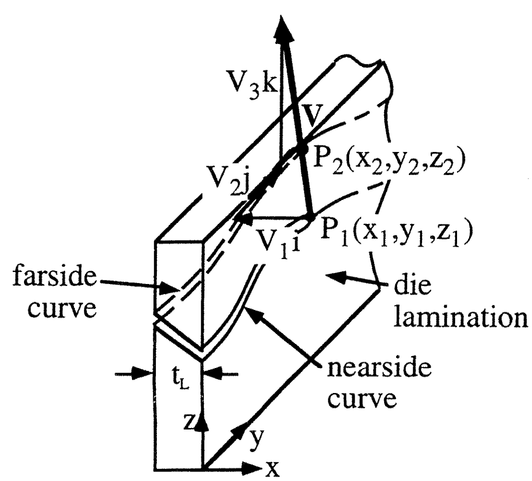


Figure 2 - Die lamination profiled edge made by 3-D beveling.

III. Geometric Error Introduced by Straight Bevel Approximation:

By observing the X-Z plane cross section of a die lamination in Figure 3, it is evident that the straight bevel of the profiled edge will deviate from the desired die surface. During the grinding and polishing operations on the die surface, this deviation or shape error is increased for convex cross-sectional profiles, as shown in figure 3a, because of material removal. For the same reason, i.e. material removal, the shape error is decreased for concave cross-sectional profiles as shown in Figure 3b. Therefore, the extent of material removal during the smoothing operation directly affects the shape integrity of the forming die. The standard method for determining the die shape error is to directly measure the surface with a coordinate measuring machine and then compare that data with the reference CAD shape.

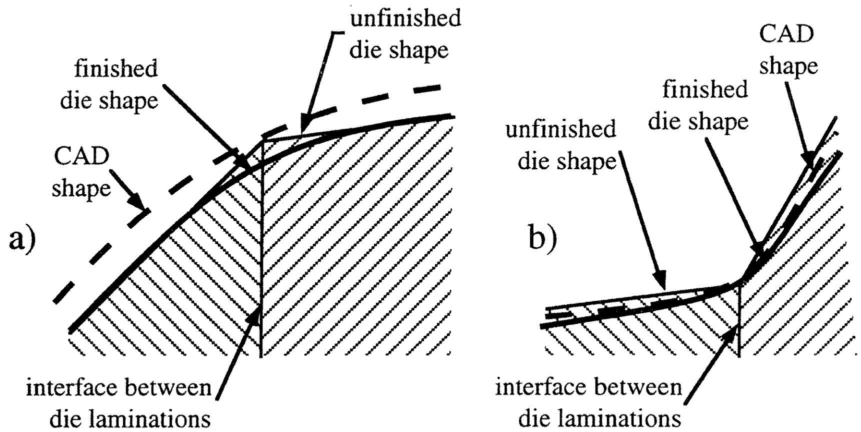


Figure 3 - Shape error due to smoothing of a) convex and b) concave die geometries

Instead of direct measurement, the maximum error introduced by the straight bevel cutting of the die lamination profiles can be estimated by considering the cross-sectional geometry from the CAD database as shown in Figure 4. The actual cross-sectional curve of the die surface model can be determined using currently-available CAD software for comparison with the straight bevel. The task of extracting this curve is very cumbersome. A simpler way to determine the maximum shape error is to estimate the die's cross-sectional curve between points (x_1,y_1) and (x_2,y_2) with a parabola. A parabola is used because it easily curve-fits 2 coordinate points with known slopes. This parabola is defined by bevel end coordinates (x_1,z_1) and (x_2,z_2), and the corresponding instantaneous x-z slopes $\frac{\partial z_1}{\partial x_1}, \frac{\partial z_2}{\partial x_2}$. The coordinates and slopes are easily obtainable with many CAD programs (e.g. ProEngineer™). The general equation of a parabola in the X-Z plane is

$$(x - h)^2 = 4 \cdot p \cdot (z - k) \qquad (2) \qquad \text{if it opens upwards, i.e. } \frac{\partial z_1}{\partial x_1} < \frac{\partial z_2}{\partial x_2}, \text{ and}$$

$$(x - h)^2 = -4 \cdot p \cdot (z - k) \qquad (3) \qquad \text{if it opens downwards, i.e. } \frac{\partial z_1}{\partial x_1} > \frac{\partial z_2}{\partial x_2}$$

where: p = parabola's focal length and
(h,k) = the vertex coordinates.

Fitting a parabola to the die lamination cross-section shown in Figure 4 yields the following substitutions into equ. 2;

$$h = x_1 - 2 \cdot p \cdot \frac{\partial z_1}{\partial x_1}; \quad k = z_1 - \frac{(x_1 - h)^2}{4 \cdot p}; \quad p = \frac{x_2 - x_1}{2 \cdot \left(\frac{\partial z_2}{\partial x_2} - \frac{\partial z_1}{\partial x_1} \right)} \qquad (4)$$

and the following substitutions into equ. 3;

$$h = x_1 + 2 \cdot p \cdot \frac{\partial z_1}{\partial x_1}; \quad k = z_1 + \frac{(x_1 - h)^2}{4 \cdot p}; \quad p = \frac{x_2 - x_1}{2 \cdot \left(\frac{\partial z_1}{\partial x_1} - \frac{\partial z_2}{\partial x_2} \right)}. \tag{5}$$

The slope **m** of the line which passes through points (x_1,y_1) and (x_2,y_2) is found by the relation

$$m = \frac{z_2 - z_1}{x_2 - x_1}. \tag{6}$$

The point (x_p,y_p) on the parabola with the same slope is found by setting the first derivative $\frac{\partial z}{\partial x}$ of equ. 2 and equ. 3 equal to **m**. If the parabola opens upward, then

$$x_p = h - 2 \cdot p \cdot m \text{ and } z_p = k - p \cdot m^2. \tag{7}$$

If the parabola opens downward, then

$$x_p = h + 2 \cdot p \cdot m \text{ and } z_p = k + p \cdot m^2. \tag{8}$$

To find the distance **e** between the line passing through (x_1,y_1) and (x_2,y_2) and the parallel line passing through (x_p,y_p), a line is constructed through (x_p,y_p) which is perpendicular to the other two lines, i.e. slope $= -\frac{1}{m}$. This perpendicular line intersects the (x_1,y_1) and (x_2,y_2) line at point (x_g,y_g). The values of this new intersection point are found from the equations

$$x_g = \frac{m \cdot x_1 + \frac{x_p}{m} - z_1 + z_p}{m + \frac{1}{m}} \text{ and } z_g = z_1 + m \cdot (x_g - x_1). \tag{9}$$

The maximum distance **e** between the parabola and the straight line representing the bevel represents is the largest error. It is calculated with the equation

$$e = \sqrt{(x_p - x_g)^2 + (z_p - z_g)^2} \tag{10}$$

If desired, the error estimated with equ. 10 can be expressed as a function of lamination thickness $\mathbf{t_L}$ so that an optimization procedure for choosing the thicknesses, interface placement, and orientation of the laminations can be implemented. The goal of this procedure would be to minimize the overall bevel approximation error.

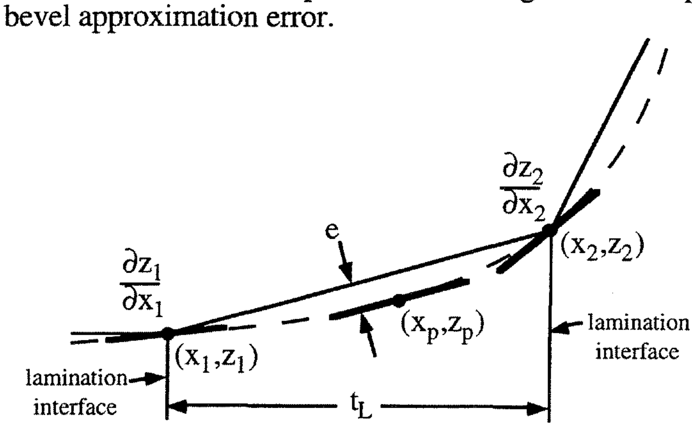


Figure 4 - Shape error estimation of a beveled die lamination

IV. Bevel Cutting Methods For Die Laminations

Once the intersection curves that define the top profiled-edge bevels of each lamination are extracted from the CAD model, the corresponding die laminations can then be fabricated. This machining database can then be used to either cut new die lamination blanks or to recut existing die laminations into a new shape. Machining bevels into the die lamination edge can be accomplished by several methods. As seen in Figure 5a, the flute-edge of a standard endmill mounted in the spindle of a 4 or 5-axis (X, Y, and Z-translation, Y and Z-rotation) CNC milling center can be used to cut bevels into a suitably-fixtured die lamination. This machining method relies on the application of high machining forces to make a wide cut in the workpiece. To minimize the amount of material removed while cutting the bevel, a very narrow kerf can be cut into the die lamination using unconventional machining methods like traveling-wire EDM, abrasive water-jet cutting, plasma-arc cutting, or laser cutting (both CO_2 and Nd:YAG) as seen in Figure 5b. Each of these methods require CNC-controlled axes that move in X, Y, Z translation, and Y, Z rotation.

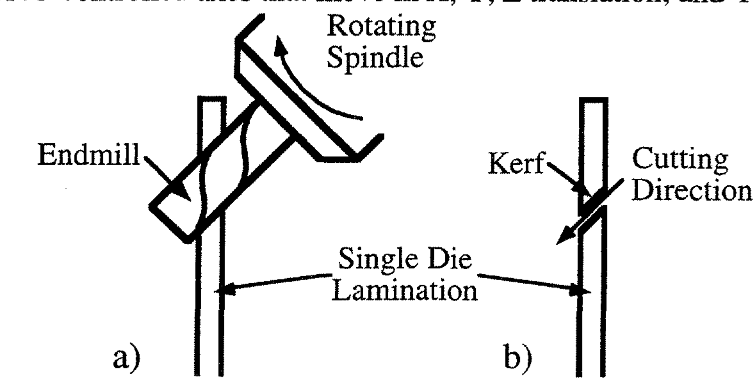


Figure 5 - Cutting bevels into die laminations by a) flute-edge endmilling and b) by unconventional machining methods.

The important characteristics of any bevel cutting method are maximum achievable bevel angle, maximum cutting feedrate (speed), cut surface quality, cutting accuracy, amount of material removed, tool wear, extent of metal burring, and machine cost and the effect of material hardness on cutting speed. Quantifying the performance specifications of each of the aforementioned bevel-cutting methods is necessary so that the most suitable one(s) for machining PEL die laminations are identified.

Suitable methods for cutting bevels include machining with the flute-edge of an endmill, abrasive water jet cutting, plasma-arc cutting, and laser cutting. Although wire-cut EDM produces kerfs of excellent quality and accuracy, an extremely slow cutting feedrate makes it impractical for bevel cutting. The other cutting methods were investigated in detail through a series of bevel cutting experiments to determine how rapidly and accurately each one will machine steel PEL laminations. The lamination material used for all cutting experiment was 1.47 mm thick SAE 1010 cold drawn steel sheet. Steel was used for the cutting experiments since it is arguably the most common material for sheet metal forming dies [8]. The basis of evaluation for each beveling method will be the quality characteristics of the bevel cut that it makes. The quality characteristics are defined in figure 6.

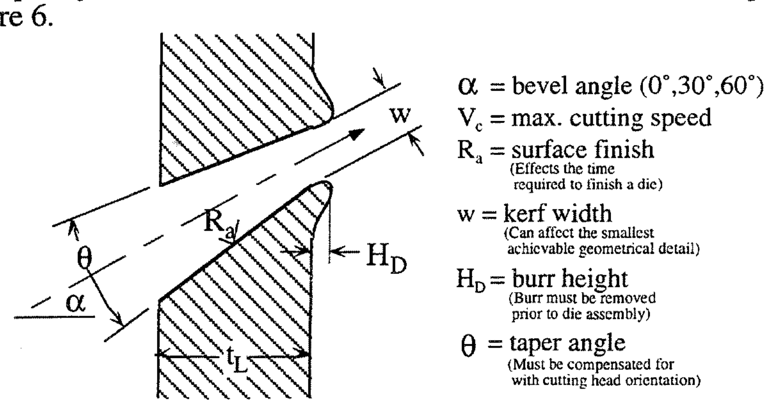


Figure 6 - Quality characteristics of a bevel cut.

The following equipment was used for the bevel cutting experiments:

- a Cincinnati-Milacron 3-axis machining center with a 6.4 mm diameter 4-fluted carbide endmill.

- An OMAX JetMachining System with a 0.76 mm cutting nozzle diameter and 80 grit garnet abrasive, i.e. 0.267 mm average particle size.

- a Hypertherm HD-1070 HyDefinition Plasma-Arc unit with O_2 plasma & shield gas, 130 volt DC output voltage and 30 amp output current.

- a Laserdyne 5-axis, model 780, CNC laser cutting system with a Lumonics JK704 Nd:YAG laser (maximum 400 watts of average output power).

Further details on all of these cutting experiments can be found in reference [9].

Summary of Bevel Cutting Methods:

For the purpose of comparing the candidate bevel cutting methods, the beveling performance measures (cutting force, maximum f_m, maximum α, taper angle, kerf width, machining burr height, and kerf surface finish) of each method, with process parameters set to their optimal levels, are listed in table 2. Plasma-arc cutting is noticeably absent from this table since it became apparent that this method was not suitable for bevel cuts. Bevels at angles up to 45° yielded very large tapers (>10°) in the kerf, excessive dross (H_D=0.9 mm) which was welded to the metal, and a large Heat Affected Zone (HAZ). The large HAZ caused the cut edge of the lamination to warp slightly. The maximum bevel angle achieved was 60° but the kerf edge closest to the cutting nozzle was consistently obliterated from an over-zealous oxidation (self-burning) of the metal during cutting. Consequently, the following comparisons are only made between flute-edge endmilling, AWJ cutting and laser cutting:

- Flute-edge endmilling involves the application of a high cutting force with a cutting tool to remove the unwanted lamination material. The higher cutting forces significantly deflect the cantilevered portion of a lamination being beveled. AWJ cutting and laser cutting, i.e. non-contact cutting methods, cause negligible deflection to the lamination.
- All three cutting methods are capable of high cutting speeds but the maximum speed is highly dependent upon the material composition and hardness with flute-edge endmilling and AWJ cutting. The maximum laser cutting f_m is only dependent on laser power, i.e. proportional to q_{laser}, which means that higher cutting rates than that listed in table 2 are achievable.
- The maximum bevel angle for all three methods is around ±80°.
- The kerf from AWJ cutting has a very large, consistent taper of around 10° for all bevel angles that must be compensated for during bevel cutting. Laser cutting creates only a slight kerf taper. Flute-edge endmilling leaves no appreciable kerf taper unless there is significant deflection of the lamination and cutting tool during beveling.
- The width of the kerf affects the smallest radius of curvature achievable for a PEL's profiled edge. Of the three beveling methods, laser cutting creates the narrowest kerf. The kerf from AWJ cutting is also narrow but not as much as that cut with a laser. The kerf width from endmilling is much larger, i.e. the diameter of the cutting tool.

• Flute-edge endmilling leaves a very large machining burr, especially at larger bevel angles. AWJ cutting and laser cutting, on the other hand, yield much smaller machining burrs. Laser cutting with a pure oxygen assist gas yields a porous, brittle edge burr (i.e. iron oxide) which is easily removed from the cut lamination without having to grind it off.

• Flute-edge endmilling yields the smoothest surface finish of all the methods although the finish deteriorates at higher bevel angles from more machining chatter. AWJ cutting offers the most consistent surface finish for all bevel angles.

Table 2 - Comparison Table of Bevel Cutting Methods using Optimal Parameter Settings

	Cutting Method	**Flute-Edge Endmilling**	**Abrasive Water Jet Cutting**	**Nd:YAG Laser Cutting with Hard Optic Beam Delivery**
	Cutting Force	Significant (lamination bends 1-2 mm at high bevel angles)	Small (momentum transfer from abrasive)	Negligible
	Maximum f_m for 0° bevel cut (meters/min)	0.46 (affected by material hardness and composition)	0.31 (affected by material composition)	0.44 for q_{laser}=0.3 kW (max. $f_m \propto q_{laser}$)
	Maximum α	$\tan^{-1}\left(\frac{L_f}{t_L}\right) = 85°$	at least 75°	80°
	Kerf Taper Angle θ	None	+10°	-1° to -2°
Nominal 30° Bevel	w (mm)	6.4 (tool Ø)	0.7	0.1
	H_D (mm)	2.8	0.1	0.04 (porous edge burr)
	R_a (μm)	0.7	3.4	4.4

Based on the preceding analysis and discussion, the authors rank the suitability, i.e. best to worst, of these three bevel cutting methods for cutting steel laminations as follows:

1) Nd:YAG laser cutting because feedrate is only dependent on laser power, tool wear is non-existent, cutting force is negligible and the kerf is the narrowest of all,

2) Abrasive water jet cutting since feedrate is dependent on material hardness and the kerf taper is the largest among the three methods, and

3) Flute-edge endmilling since the cutting force, kerf width, edge burr, and feedrate's dependency on material hardness is the greatest overall.

V. Machinery for Fabricating PEL Dies:

As with CNC-machining of a sheet metal forming die, the two most important specifications of equipment used to fabricate PEL dies are to 1) get as close to near net shape as possible thereby minimizing the need for a post-grinding or finishing operation and 2) accomplish this task as fast as possible. The key to meeting these specifications are the correct choice of a bevel cutting method, as discussed is the previous section, and the efficient handling of die laminations during the cutting. There are two options for efficiently cutting PEL die laminations: retrofitting a commercially-available cutting machine or developing a dedicated, stand-alone machine.

For compound beveling of PEL die laminations, a 5-axis machining center (e.g. 3 translational & 2 rotational axes) is required to correctly position the cutting nozzle during the profiling process. Currently, there are numerous 5-axis conventional machining centers, and a few laser and AWJ machining centers that can be used to machine compound bevels. Using any of these 5-axis machining centers, a die lamination blank must first be vertically secured to the machine's workbed and then the profiled-edge is machined. The die lamination can be handled manually or the machining center can be retrofitted with an automatic handling mechanism.

Five-axis laser machining centers are much more expensive than comparable AWJ or CNC machines. For example, a Laserdyne Model 780 BeamDirector™ 5-Axis laser machining center with a Lumonics JK704 laser currently sells for around $625K. Other laser machining centers vary in price from $500K to $700K. In contrast, a Cincinnati-Milacron Sabre-1000 CNC 3-axis vertical machining center retrofitted with a Tsudakoma TTNC-201 tilting rotary table that has a similar work volume as the Laserdyne system sells for around $120K. For $180K, a company an purchase a Jet Edge® model 55-30 AWJ cutting system that's mounted to a 5-axis, robot-controlled gantry table and has a similar work volume as the laser system. With any of these systems, the estimated cost of a custom-built lamination handling mechanism has not been added to their overall cost.

Dedicated PEL Die Fabrication Machine:

Both conventional CNC and laser machining centers are designed for general industrial use and not optimized for cutting die laminations in terms of speed, cost, and factory floor space required. Taking into account the high cost of commercially available equipment and the added cost of a custom-built lamination handling mechanism, a dedicated stand-alone machine for fabricating PEL dies is proposed by the authors as a cost-effective alternative to retrofitting currently-available 4 and 5-axis cutting machines. This specialized apparatus will be called a Die Lamination Profiling (DLP) machine. For industry to embrace the PEL die method, these machines will be required to fabricate dies in a rapid and efficient manner. Several machine DLP machine concepts have already been developed.

VI. Propensity for PEL Die Delamination:

If the PEL die laminations are bonded together then the composite structure becomes a continuous die. To keep the PEL die easily re-machinable, the die laminations are simply clamped together with a rigid frame as shown in Figure 1b. In a clamped configuration, individual laminations have a propensity to delaminate, i.e. separate from adjacent laminations, by elastically deforming or buckling under the high forming loads encountered. As seen in Figure 7a, the die shape changes when a lamination(s) bends elastically resulting in dimensional changes to the parts formed. For this reason, it is important to investigate the elastic bending and buckling behavior of a clamped lamination subjected to typical forming loads.

Excessive deformation of any of the clamped die laminations beyond a certain maximum value, i.e. $\delta > \delta_{max}$, will be considered a die failure. Ideally a PEL die should emulate a continuous die whose surface deformation is essentially negligible (e.g. 0.01 mm for a steel die). However, a more practical design requirement for PEL dies is to make sure that the dimensions of the formed part are within the specified tolerances. The maximum deformation value (δ_{max}) of a die lamination is explicitly determined from this requirement.

Referring to Figures 7a and 7b, a group of deflected laminations (due to high forming loads) can be roughly modeled as cantilevered Euler beams in a parallel configuration. This assumes that the frictional shear forces at the interfaces between adjacent laminations are negligible. The deflection δ of a single rectangular lamination (see Figure 8a) can be estimated using the relation

$$\delta = \frac{4 \cdot F_{bending}}{E \cdot b}\left(\frac{a}{t}\right)^3 . \qquad (11)$$

where: a = lamination height
b = lamination width
t = lamination thickness

E = tensile elastic modulus of the lamination material

$\mathbf{F}_{\mathbf{bending}}$ = horizontal component of the lamination's total forming load.

By rearranging equation 11, the spring rate $\mathbf{k}_L$ of the lamination is then

$$k_L = \frac{F_{bending}}{\delta} = \frac{b \cdot E}{4}\left(\frac{t}{a}\right)^3. \qquad (12)$$

The mode of mechanical failure of a lamination from the vertical component of the forming load $\mathbf{F}_{\mathbf{buckling}}$ will be some form of buckling behavior. As stated by Timeshenko et al., " in the calculation of critical values of forces applied to the middle plane of a plate at which the flat form of equilibrium becomes unstable and the plate begins to buckle, the same methods as in the case of compressed bars can be used" [10]. Therefore, the critical buckling load $\mathbf{F}_{\mathbf{b,critical}}$ for the lamination shown in Figure 8a can be estimated using the Euler column buckling formula

$$F_{b,critical} = \frac{k \cdot E \cdot b \cdot t^3}{12 \cdot a^2} \qquad (13)$$

where: k = factor that depends on the end support conditions of lamination.

If the lamination can be modeled as a simple cantilever beam then k is 2.47. If the movement of it's upper edge is restricted horizontally then k is 20.2.

The forming forces on a lamination consist of an effective normal load $\mathbf{F}_n$ and a perpendicular frictional load $\mu \cdot F_n$ at the lamination (die) and sheet metal interface where μ is the frictional coefficient. These loads are shown in Figure 7. The total forming load $\mathbf{F}_T$ has a magnitude of $F_n \cdot \left(1+\mu^2\right)^{\frac{1}{2}}$. As shown in Figure 8b (vector diagram), F_T typically points inward to the die. This is a desirable situation since convex portions of the laminated die will tend to be pushed together during forming. In terms of F_T, the bending and buckling loads are $F_T \cdot \sin\left(\alpha - \tan^{-1}\mu\right)$ and $F_T \cdot \cos\left(\alpha - \tan^{-1}\mu\right)$, respectively.

As an example, let us investigate the bending and buckling propensity of one particular lamination in the male PEL die described in reference [1]. The lamination chosen is located 2.8 centimeters in from the edge along the X-axis. It's profiled edge forms half of the upper bend radius for one of the benchmark part side walls. A maximum forming load of 50 kN is predicted by the FEA simulation of the forming process. Since the upper bend radii on the male die takes most of the total forming load, the estimated maximum normal force that this particular lamination experiences is approximately 6.0 kN. Additional data on the lamination is **a**=1.9 cm, **b**=6.4 cm, $\mathbf{t}_L$=1.47 mm, **E**=200 GPa, μ=0.2 (for greased steel on steel) and α=bevel angle=30°. As a result the bending and buckling components of the total forming load are 2.0 and 5.8 kN, respectively. Furthermore, the prescribed dimensional tolerance of the benchmark part is ±0.1 mm. Since this lamination is backed by 35 adjacent laminations of similar size in the direction of the bending load, the estimated bending deflection is only 0.04 mm according to equation 11. This deflection is well below the die's dimensional tolerance. This simple deflection analysis doesn't even take into account the symmetrical loading on the male die which will tend to counteract the high forming load applied to this sample lamination. Finally, if we assume a worst case buckling scenario where the lamination is unsupported on it's top edge, the critical buckling load is 23 kN according to equation 13. This value is well above the maximum above the maximum assumed buckling load of 5.8 kN so that buckling will not be a problem.

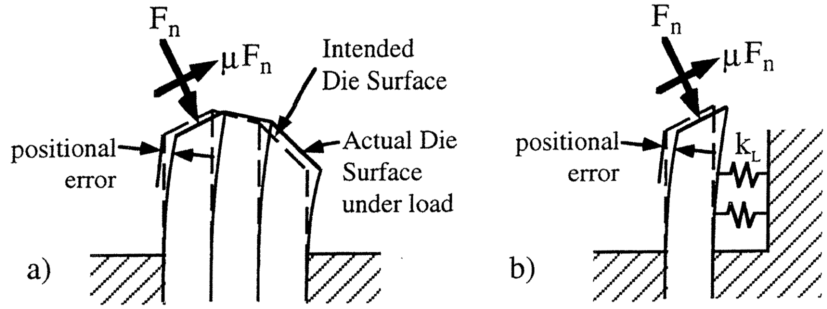


Figure 7 - a) Group of die laminations subjected to forming loads and b) modeled as cantilevered Euler beams in a parallel configuration

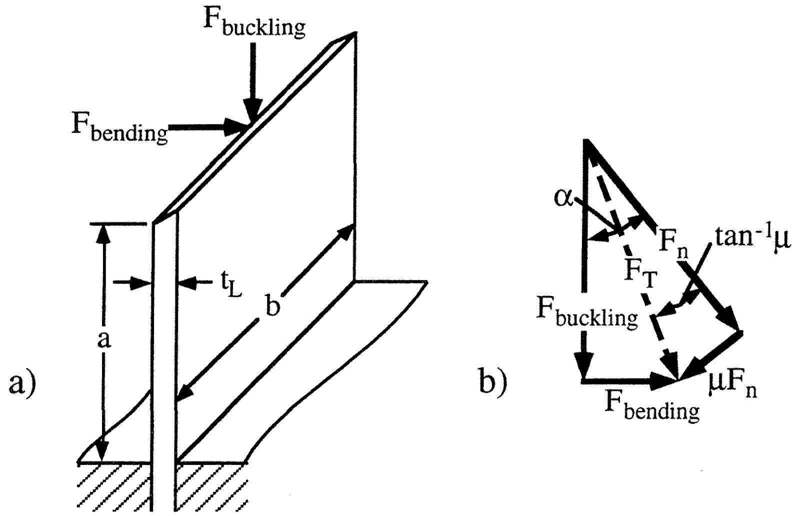


Figure 8 - a) a single rectangular die lamination subjected to bending & buckling loads and b) vector diagram of the said loads.

Conclusions and Planned Future Work

In terms of handling laminations during processing, registering and clamping the laminations into a rigid die, and reshaping the die during the tooling development process, the PEL method for fabricating sheet metal forming dies improves upon the current method of stacking and bonding contoured laminations. In this paper, the general procedure for extracting the machining instructions for each die lamination is outlined for die shapes that require either 3-D or simple planar beveling. A method for easily estimating the geometrical error caused by the straight bevel approximation of each machined lamination is also introduced. Three cutting methods - machining with the flute-edge of an endmill, abrasive water jet cutting, and especially Nd:YAG laser cutting - are shown to be viable techniques for machining bevels into die laminations. Finally, in a completely assembled PEL die, the propensity for die delamination is shown to be more sensitive to bending failure than buckling failure.

Future developmental work to help establish PEL dies as a viable alternative to conventional CNC-machining of sheet metal forming tools includes:

• developing a algorithm that will determine the best orientation of the PEL laminations, with respect to the die shape, to minimize the overall error from the straight bevel approximation.

- bevel cutting experiments with other die materials like tool steel, Invar, aluminum, epoxies, and certain other plastics suitable for sheet metal forming

- developing a Die Lamination Profiling machine.

- an investigation of all available methods for permanently bonding PEL laminations together into a solid tool (e.g. diffusion-bonding).

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