

A Comparison of Rapid Fabrication Methods for Sheet Metal Forming Dies

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The need for rapid, low-cost die fabrication and modification methods is greater than ever in the sheet metal forming sector of industry. Consequently, three fabrication methods, suitable for rapid die development schemes, are being compared experimentally based on cost, lead-time, shape resolution and flexibility issues. The candidate methods include CNC-machining a solid billet of material (standard method), assembling and clamping an array of profiled-edge laminations (PEL), and configuring and clamping a matrix of closely-packed pins (discrete die). A matched-set of forming dies was made using each of the candidate fabrication methods for stamping an FEA-verified benchmark part out of steel sheet. Based on the stamping experiments, a PEL die is shown to be similar to CNC-machined dies except that most tooling accessibility problems are eliminated, die geometry limitations are reduced and faster fabrication is possible for harder tool materials. When compared with CNC-machined dies, the discrete die method limits part shape fidelity, maximum forming loads, die geometry and blankholder incorporation. However, the discrete die method excels over the other two methods in terms of lower cost and faster fabrication time. The results of this study make a strong case for the sheet metal forming sector of industry to actively implement the PEL and discrete die methods in their manufacturing operations.

1 Introduction

Womack (1991) has noted that as manufacturing companies adopt "lean production" techniques to stay competitive in the world economy, there is an effort afoot in the sheet metal¹ forming sector of industry to reduce the lead time and investment costs of tooling development. Such an effort by industry to reduce lead-time and cost is sorely needed because the development of dies used to form sheet metal parts is extremely time-consuming and expensive. The following examples support this point:

In the auto industry, construction of forming dies for sheet metal is the longest lead time element of any new major vehicle program (Walker, 1993). A new major vehicle program typically requires stamping dies for around 100 sheet metal parts. In one particular instance, a major U.S. die builder designed and fabricated 11 prototype (kirksite) and production (cast iron) die sets made for stamping the left and right quarter panels of a mid-size car. Wagner (1995) claims that the die sets, which will stamp about 1.5 million panels during their lifetime, cost the customer \$3,200,000 and took over 60 weeks to complete.

For a particular U.S. aerospace company, a Richlite die (paper laminates impregnated with phenolic resins) used for stretch forming aircraft body panels costs \$19,000 and takes 90 hours to fabricate (including tool design effort) on average (Nardiello, 1995). Since each F-14 fighter aircraft manufactured by this company has about 300 stretch-formed fuselage skins, the total cost of stretch forming tooling used for only about 750 planes was over \$5,000,000.

A leading air conditioning equipment manufacturer uses a set of four stamping dies (draw, trim, flange, and side pierce) to

stamp a 0.55 m × 0.44 m × 0.3 m draw base pan for a residential air-conditioning unit. According to Dastidar (1995), these dies, which will stamp 1,000,000 panels during their lifetime, took 14 weeks to design and fabricate (over 50 percent of time due to internal delays) at a cost of \$150,000.

The high cost and long lead-times of die development can be blamed on the traditional trial and error procedures used by skilled die builders to obtain the correct tooling shape and forming conditions that will yield the desired part shape (Siekerk, 1986).

Nakagawa (1994) has stated that "although the rationalization of the design and manufacturing processes has helped reduce the manufacturing time substantially, the time needed to correct the die after trial forming has yet to be shortened." This represents about 40 percent of the total die development time. As shown in Fig. 1, the application of closed loop process control to sheet metal die development is an alternative approach to tooling design that can dramatically reduce the time needed to arrive at the correct die shape. Closed-loop process control incorporates the newest software tools, hardware, and die fabrication methods. Webb (1991) and Hardt (1982) have developed a closed-loop approach that treats the complex material deformation of the forming process as a system identification problem where the tooling-part transformation is developed as a spatial frequency domain transfer function. Ousterhout (1991) has shown experimentally and Karafillis (1992) through FEA simulations that such a transfer function can be used to implement closed-loop process control of 3-dimensional sheet metal forming via rapid die redesign. Karafillis (1992, 1994) has also shown how the correct tooling shape and binder design can be found with FEA-based inverse springback calculations. Process control of this sort takes the place of the time consuming trial-and-error procedure. Required shape modifications of the die forming surfaces will be based on a closed-loop shape control algorithm thereby obviating the subjectivity of experienced tool makers and tooling engineers.

Even using the aforementioned closed-loop process control procedure, significant cost and lead-time reductions with die

¹ For the sake of clarity, sheet metal is defined as any piece of uniform thickness metal less than 6.4 mm thick characterized by a high ratio of surface area to thickness (Semiatin, 1993).

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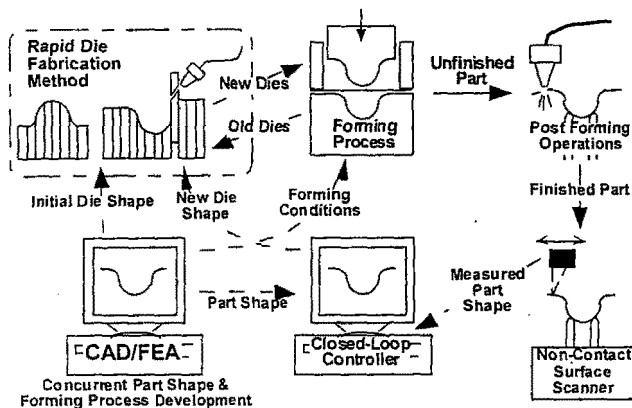


Fig. 1 Future tooling development system that incorporates closed-loop shape control

development cannot be realized unless faster and cheaper die fabrication and modification methods are implemented. For this reason, the die fabrication and modification method used in a modern die development program should ideally be both rapid and low-cost. The purpose of this paper is to identify and evaluate rapid, low-cost methods by:

- describing an experimentally-based comparative study of three candidate methods that are identified as rapid and low-cost
- discussing the successes and failures of forming sheet metal parts with sets of dies made by each candidate method
- making comparisons between each of the candidate methods based on cost, lead-time, flexibility and accuracy issues and
- formalizing the conclusions of the comparative study for use by die designers.

2 Rapid and Low-cost Die Fabrication Methods

Which die fabrication methods can be considered both rapid and low-cost? One key aspect of any method that fits these two criteria is the elimination of as many intermediate processing steps as possible, especially the need for a model of the intended forming surface. In other words, it is best to create the rigid forming die directly from the computer model without having to first create a model of mold. This is the main criteria used in choosing particular fabrication methods for investigation in this study. The remainder of this section explains the authors choice of three candidate methods.

CONTINUOUS (Monolithic) DIES: Of the continuous die fabrication methods, *CNC-machining a solid billet* (shown in Fig. 2a), is chosen for investigation. Although casting and/or EDM are frequently used to make forming dies, they are generally more expensive and time-consuming than the standard industry method of CNC machining. More importantly, a cast die requires a model and a mold during fabrication and an EDM die needs an inverse shaped electrode. A die made directly by rapid prototyping methods appears to be a promising method but currently the machinery is very expensive (\$100K to \$500K), build times are relatively long (>8 hours) compared to CNC-machining, sizes are limited by small work volumes of the machinery, and the material properties of RP models are only sufficient for low forming force applications (Aubin, 1994).

LAMINATED DIES: As shown by Kunieda et al. (1984), Glozer et al. (1993), Pridham et al. (1993), Walczyk and Hardt (1994), Dickens et al. (1996) and Engler et al. (1997), laminated forming dies can be created directly from a computer model of the intended forming surface. Because machining of

laminations used in a laminated die is only done in 2-dimensions, this type of die construction technique has advantages over CNC-machining a solid billet in terms of fabrication time and die shape flexibility. For these reasons, *laminated forming dies* are also chosen for investigation. However, the current method—vertically stacking and bonding an array of contoured laminations that are oriented in a horizontal plane—has several disadvantages which severely limit its use as a rapid fabrication method including difficulties with lamination handling, registration, and shape modification (Walczyk, 1996).

For these reasons, another lamination-based method called the *Profiled-Edge Lamination* or simply PEL method (see Fig. 2b), developed by Walczyk and Hardt (1994), has been chosen as a candidate method. The PEL die method improves upon all of the shortcomings associated with stacking and bonding contoured laminations by simply reorienting the laminations to a vertical plane, profiling the top edge of each lamination according to the die shape required, and then clamping the entire lamination array from the side. In addition, the profiled edges are beveled to eliminate the stair-stepped surface normally associated with laminated dies.

DISCRETE DIES: As shown by Ousterhout (1991), a reconfigurable discrete die can be used as a rigid tool for sheet metal forming. Furthermore, its shape is based directly on a CAD model of the die surface. Because of its reconfigurable and universal nature (i.e., relative positions of pins can be continuously varied), setting a discrete die is potentially quicker and lower cost than CNC-machining. Even considering the ease with which the die shape can be set, a discrete die consisting of separated pins is not chosen since this configuration cannot withstand the forming pressures encountered with most sheet metal forming processes. For this reason, a *discrete die with closely-packed pins*, as shown in Fig. 2c, is chosen as the last candidate method.

In summary, the following fabrication methods were chosen as candidates for further investigation and eventual comparison to one another in terms of suitability in a die development scheme for sheet metal forming:

- CNC-machining a solid billet of material
- Assembling and clamping an array of profiled-edge laminations and
- Configuring and clamping a discrete die consisting of a closely-packed matrix of pins.

For the remainder of this paper, the resulting tools will simply be referred to as a CNC-machined die, a PEL die, and a discrete die, respectively.

Three sets of matched-dies have been designed and fabricated to stamp a benchmark sheet metal part. By fabricating each die set and then using it to stamp benchmark parts, objective comparisons can be made between the three candidate fabrication methods. Results and conclusions drawn from this comparative study will allow manufacturers that must deal with tooling

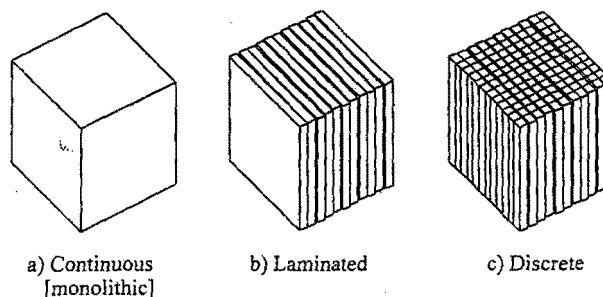


Fig. 2 Construction methods for rigid dies used in sheet metal forming include (a) continuous (b) laminated and (c) discrete dies

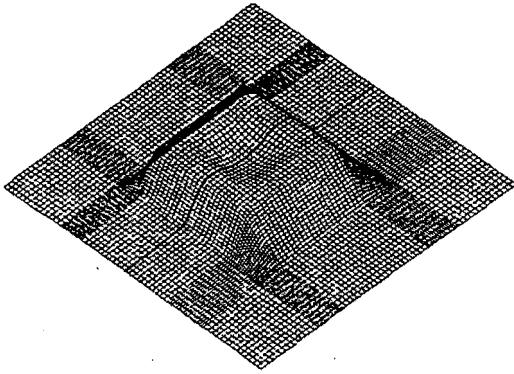


Fig. 3 CAD model of the comparative study benchmark part

development to realistically evaluate which rapid fabrication methods fits best into their flexible manufacturing system, especially those that are considering a closed-loop die development scheme.

3 Comparative Study Details

Standard processes and practices of commercial sheet metal forming were used for all experimental work. From a survey by the Fabricators & Manufacturers Association, International, i.e., FMA (1994), matched-die forming with restrained blank edges was found to be one of the most common processes used to stamp sheet metal parts. Consequently, it is used in the study. This required that a matched die set be fabricated using each of the candidate methods and also a universal blank holder. The benchmark part shape is designed with CAD and verified with FEA. A custom-written CAM software is used to generate the machining instructions needed for fabricating each of the required forming dies. The actual forming is done in a hydraulic press which is common to the sheet metal forming sector of industry. Finally, the formed parts are measured using a Coordinate Measuring Machine (CMM).

Comparisons made between each of the three candidate rapid fabrication methods are primarily based on lead-time and cost. Ten criterion used for this study are:

- (1) Time required to fabricate or configure the dies into the shape of the benchmark part
- (2) Time required to reshape or reconfigure the dies into a new die shape
- (3) Capital cost of the machinery required for die fabrication
- (4) Cost of raw materials used to fabricate the dies
- (5) Cost of process consumables (e.g. cutting tools, power) used during die fabrication
- (6) Shape fidelity of parts formed with the dies
- (7) Limitations to die geometry imposed by the fabrication method
- (8) Limitations on forming load
- (9) Limitations on die size
- (10) Limitations on incorporating a blankholder.

Criterion 6 through 10 do not deal with the cost and/or lead-time of tooling development directly but rather have an indirect effect. This will be discussed in a later section.

4 Design of a Benchmark Part

As shown in Fig. 3, a shallow pan that's $7.0 \times 7.0 \times 2.0$ cm with 4 different wall angles (45 deg, 52 deg, 60 deg, and 68 deg), inner bend radii of 3.2 mm, and a central reverse curvature section serves as the benchmark part for comparing the candidate fabrication methods. The part is stamped out of 0.64 mm thick DQAK (Draw Quality Aluminum Killed) steel. This part

was designed as an AutoCAD™ wireframe model and then meshed-in with NURBS surface patches. The CAD geometry was then transferred to the ABAQUS™ FEA program (explicit analysis used) via a custom-written conversion program. An FEA model of a matched-die forming arrangement with a 15×15 cm square blank shape was used to verify that the desired part was indeed formable. Tensile tests performed on this steel established the yield strength, ultimate tensile strength, and elongation strain to be 178 MPa, 412 MPa, and 27 percent, respectively, which were used in the forming simulations. A constant binder force was evenly distributed around the perimeter of the blank. The total time to design and verify the part, and to develop engineering drawings was 4 man-days.

By design, many different forming modes are incorporated into the benchmark part. Cup drawing occurs in each of the corners. Plane strain stretching occurs in the angled walls of the pan section while bi-axial stretching occurs in the centrally-located reverse curvature section. Bending and straightening are occurring in the upper and lower corners of the pan. In this forming mode, metal is pulled from a flange, bent over a die radius, and then re-straightened.

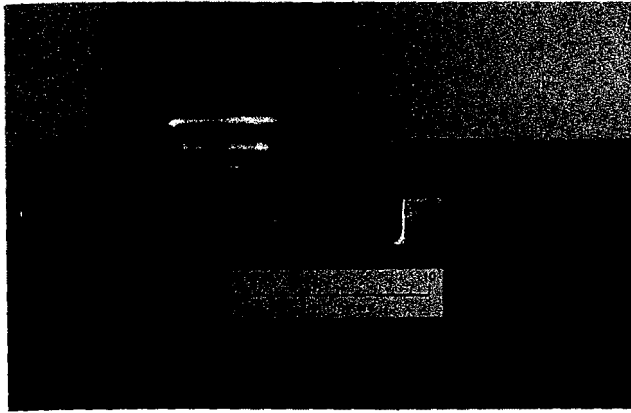
The shape and forming conditions of this benchmark part were chosen particularly to highlight the advantages and disadvantages of each different type of die construction. The plane-stretching that occurs in the angled walls creates highly localized forming pressures at the upper and lower bends of the dies. For the PEL dies, this situation is a good test of how an unbonded lamination construction resists delamination, i.e. lateral forming forces bending the plates. For the discrete dies, the high forming pressures tests the ability of a surface interpolator to prevent die pins from dimpling the part surface. Furthermore, the high forming forces are directly transmitted to the die pins, possibly causing them to slip. Forming with high forces is a good test of how well the element clamping scheme works (i.e., uniformity of forming load distribution and transmission of loads to die frame).

With all of these different forming modes occurring, the benchmark part is a challenge to form with any type of die including conventional tooling (i.e. CNC-machined die). It is asymmetrical with four different wall angles and corner conditions (X - Y plane radii). The sheet metal tends to buckle in the flange near the corners and tends to tear in the upper part of the corners, both which are considered material failures. It really can be considered a borderline part in the sense that it has a propensity for some sort of part failure (tearing, buckling) if the friction and/or binder force is too high or too low. These forming characteristics are an important test of how well unconventional die constructions (i.e., PEL and discrete dies) compare with standard CNC-machining a die in a realistic forming situation.

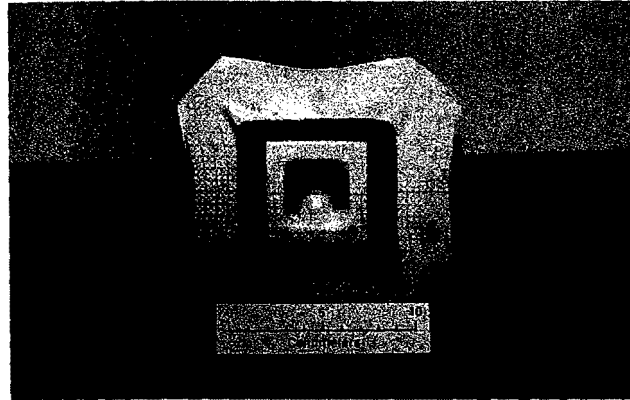
5 Fabrication of the Forming Dies

The matched-set of dies fabricated for the case study are 10.2×10.2 cm and made out of AISI 11L17 steel. A 3-axis CNC machining center was used to make the roughing and finishing cuts in the die surfaces. Finishing cuts with a ball endmill that left a scalloped surface had to be ground out using a hand-held die grinder. The die surfaces were finally polished smooth to make them suitable for forming sheet metal parts. The forming dies and a benchmark part stamped from steel sheet using these dies are shown in Figs. 4a and 4b, respectively.

A matched-set of PEL dies consisting of 1.47 mm thick steel laminations were also fabricated for the comparative study. The top profiled and beveled edge of each lamination was machined with the weaving motion of a ball endmill mounted in a 3-axis CNC machining center. After assembling the laminations into a die, the resulting top surface was ground and polished using a hand-held die grinder to as smooth a surface as possible without modifying the die shape significantly. The two lami-



(a)



(b)

Fig. 4 (a) Matched set of CNC-machined dies and (b) benchmark sheet metal part stamped with these dies

nated forming dies and a part stamped from steel sheet using these dies is shown in Figs. 5a and 5b, respectively.

As shown in Fig. 6a, a pair of high-resolution discrete dies were constructed for the comparative study. Each die consists of a 64 by 64 matrix of 1.59 mm square pins clamped from the side with a 30 ton capacity hydraulic ram. The dies can be configured in two ways: as a simple close-packed pin matrix or and as a close-packed matrix with load-carrying row dividers.

6 Sheet Metal Forming Experiments

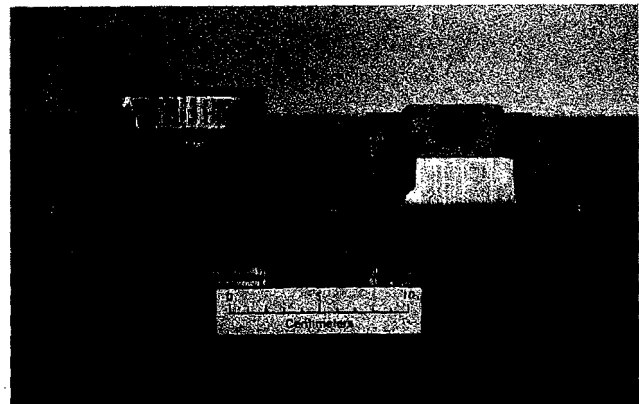
A series of steel benchmark parts were stamped out of the 0.64 mm thick sheet stock using each of the matched-die sets. As shown in Fig. 7a, the apparatus used for stamping was a hydraulically-powered universal testing machine which records force/displacement data during the stamping experiments. The edges of the sheet metal blanks were clamped in a free-floating 2-piece blankholder which was held together with 16 high-strength bolts. The blankholder, shown separately in Fig. 7b, is designed to accommodate a square blank size between 10.5 and 15.3 cm on a side. A particular binder force is achieved by tightening the blankholder bolts to a specific torque.

CNC-Machined Dies. Several sheet metal parts were formed with the CNC-machined dies using various combinations of binder force, blank shape, and lubricant. The goal was to find out which combination of forming conditions yielded the best looking part, and also to validate the FEA simulation results. The best combination was a high binder force (100 kN), low forming friction (.025 mm thick Teflon layer, $\mu < 0.10$ for Teflon on steel), and a 15 cm by 15 cm square blank-

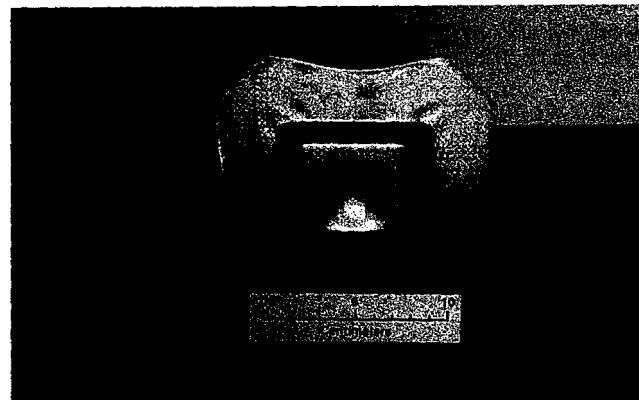
shape with 2.5 cm chamfers at each corner to minimize the corner draw-in resistance. The formed part has sharp geometric details and no perceivable failure in the sheet metal, i.e., no tearing in the upper corners or buckling within the pan section. The part also showed mild springback (around 5.7 percent in height) and some buckling in all four flange corners as predicted by the FEA analysis. The buckling is a result of unsupported regions in the sheet metal that are subjected to in-plane compressive loading. There is a noticeable dimple, roughly 2×2 cm, located in the center of the reverse curvature section of the part. Presumably, this dimple is made at the very end of the stamping operation when the dies are very close together and a machining mismatch in the die surfaces causes an unwanted coining-type operation. As seen in the force/displacement history of this part shown in Fig. 8, the maximum recorded forming load is 55 kN.

Since the use of Teflon sheets for forming parts in an industrial setting is a rather expensive and unrealistic manufacturing option, a sheet metal part was stamped using the previously mentioned forming conditions except that a viscous oil ($\mu = 0.1$ to 0.2 for steel-on steel) was used as a lubricant. As shown in Fig. 4b, this part exhibits the same details as the previous part except that the height springback was reduced (around 2.9 percent in height) and there is slightly more wrinkling in the four flange corners. The maximum forming load for this stamping run was 54 kN.

A vertical profile of this part's top surface, shown as a dark line in Fig. 3, was measured with a CMM at 0.2 mm increments in the x -direction. The average absolute height deviation and maximum height deviation of the measured part profile from the CAD profile is 0.43 mm and 2.26 mm, respectively. Since both die shapes are based on 2 surfaces created by offsetting



(a)

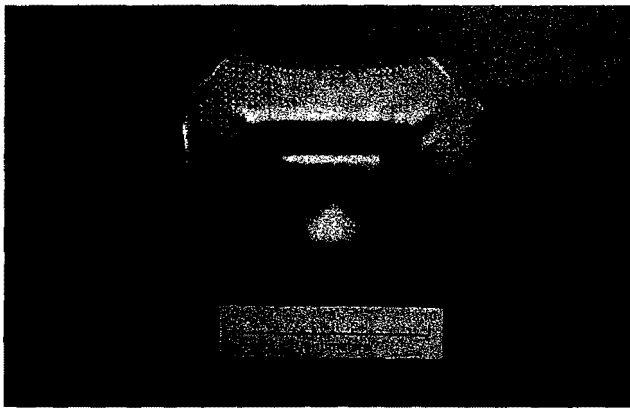


(b)

Fig. 5 (a) Matched set of PEL dies and (b) benchmark part stamped with these dies



(a)



(b)

Fig. 6 (a) Reconfigurable, high-resolution discrete die and (b) benchmark part stamped with these dies

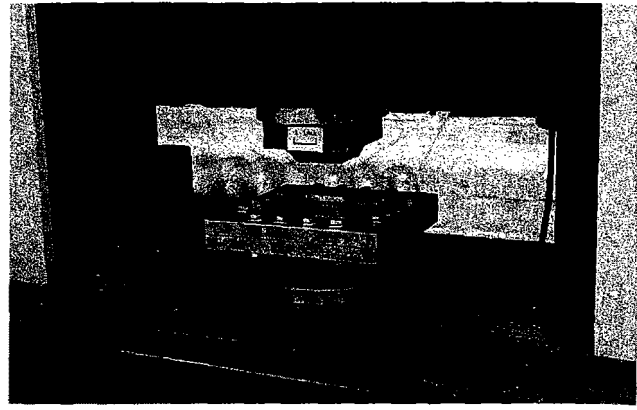
the original CAD surface model in both normal directions, most of this error is attributable to springback in the sheet metal. As part of an actual die development scheme, the shape of the dies and forming conditions would have to be modified over several stamping iterations until the desired part shape can be formed consistently.

Profiled-Edge Lamination Dies. Several sheet metal parts were formed with the ground and polished PEL dies, shown in Fig. 5a, using the same viscous oil lubricant and blank shape as the CNC die forming experiments. However, a lower binder force of 50 kN had to be used during stamping to avoid tearing in the upper corners of the benchmark part. The interfaces between adjacent elements of the PEL die forming surfaces probably account for the higher static friction and high localized stresses and, thus, the tearing problem. The height springback in this part and the maximum forming load are 2.9 percent and 55 kN, respectively.

Although there were some lamination edge marks left in the sheet metal due to lamination mismatching (see Fig. 5b), the shape fidelity of the part is as good as that of the part stamped with the CNC-machined dies (by visual inspection only). The average absolute height deviation and the maximum height deviation of the PEL part profile from the CAD profile are 0.88 mm and 3.98 mm, respectively. The height springback of the PEL part is greater than the part stamped with the CNC part probably because less stretching occurred in the sheet metal as a result of the lower binder force.

Discrete Dies.

Simple Closely-Packed Matrix. The first series of benchmark parts were stamped using the high-resolution discrete dies



(a)



(b)

Fig. 7 (a) Forming dies (CNC-machined) and blankholder mounted in a hydraulic forming press and (b) blankholder shown alone

with only simple closely-packed pin matrices, i.e., no row dividers, to see how this configuration (shown in Fig. 9a) would perform. The dies were set manually by pressing models of the benchmark part into the unclamped pin matrices and transferring the desired shape. Transferring the shape in this manner was done as a matter of convenience because automated setting methods for discrete dies was not the focus of this research. The setting operation would need to be automated (e.g., individually actuate each pin) to be practical in an industrial setting. The "set" pin matrices were then clamped with a 220 kN side force. Each matrix was designed to withstand an evenly-distributed stamping load of 67 kN before element columns began slipping.

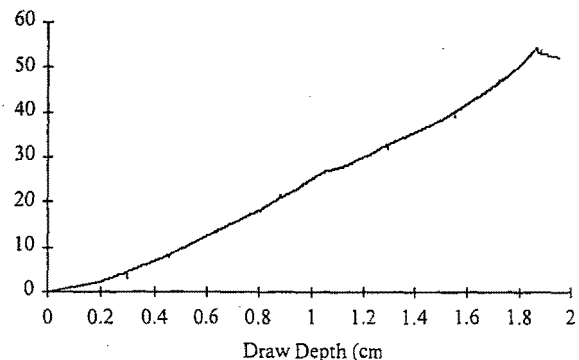


Fig. 8 Force/displacement history of a part stamped with the CNC-machined dies

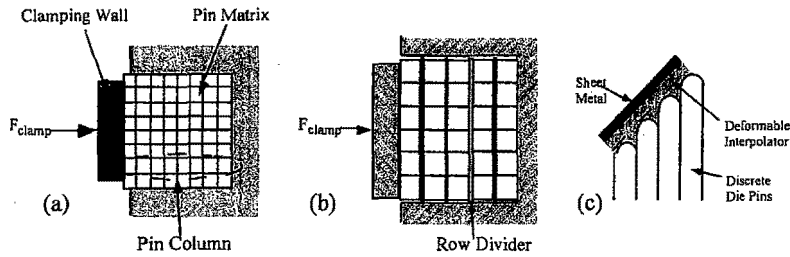


Fig. 9 (a) Clamping a close-packed pin matrix with a single compression wall (b) incorporating load-carrying row dividers that are rigidly attached to the die containment frame and (c) covering the dimpled discrete die surface with an interpolating material

After the matrices were clamped, a 1.3 mm thick layer of 460 Elvax (i.e., ethylene vinyl acetate) was performed over each of the “set” dies (as prescribed by Eigen, 1992) to act as the effective forming surface (see Fig. 9c). This elastomeric layer is called an *interpolator*. The same forming conditions used for the CNC and PEL stamping experiments were used for forming these parts.

During the first forming trial, the dies were brought together until the forming load reached a maximum of only 22 kN. When the dies were separated, it was evident that many of the pins in the upper male die (5 × 5 cm square area) began to slip at this maximum load. As this area only loads about half of the pin columns, the male die was expected to withstand a load of $67 \times 0.5 = 33$ kN. However, none of the pins in the female die slipped. Some of the protruding pins, especially in the upper four corners of the male die side, pierced through the forming interpolator and dimpled the sheet metal part. Due to the elements that slipped, the part only had the general shape of the benchmark part and not the fine detail of the CNC-machined or PEL die parts. Other parts stamped with these discrete dies suffered the same fate. Pin slippage is attributable to the highly concentrated forming loads at the upper corners.

Closely-Packed Matrix With Load-Carrying Row Dividers. The initial parts stamped with the discrete dies pointed out the inherent load-carrying limitations of a simple close-packed matrix. Because of the very high forming pressures required to stamp this part, especially at the upper corners of the male die, the high-resolution discrete dies had to be retrofitted with row dividers (see Fig. 9b) to help transfer the forming loads to the outer frame more efficiently. The row dividers are pieces of sheet metal that are placed in between rows of the pin matrix, i.e., perpendicular to the direction of clamping. Since row dividers are rigidly attached to the die frame, pin loads are transferred through the dividers.

Both discrete dies were configured to stamp the benchmark part. The pin matrices were then clamped into rigid tools with a 245 kN side clamping force. The same forming conditions used for all the previous stamping experiments were used for these runs. Without any of the pins slipping, several benchmark parts were successfully stamped using these dies with the same two Elvax interpolators.

A part stamped with these dies (60 kN maximum forming load) is shown in Fig. 6c. The discrete die part generally has less shape fidelity than the CNC and PEL parts, especially at the upper and lower bends in the pan. At each of the upper four corners (male die side), a single pin pierced through the interpolator and dimpled the sheet metal but no where else. Very little compressive buckling occurred in the flange corners but a very slight waviness can be detected in the flange around the entire draw section of the part. Presumably, the waviness is caused by a combination of the interpolator's compliance in these areas and the high in-plane compressive straining of the sheet metal that was identified by the FEA analysis. The average absolute height deviation and the maximum height deviation of

the discrete die part profile from the CAD profile are 0.98 mm and 2.45 mm, respectively.

7 Spatial Frequency Description of the Part Profile

The average absolute and maximum height deviation values are of limited use when comparing the shape fidelity of sheet metal parts stamped with different dies. A better way to compare each part's shape fidelity to the CAD shape is to map the CMM-measured 3-D coordinates into the frequency domain. As used by Webb and Hardt (1991) in their 2-D and 3-D closed-loop shape control algorithm, the interpolating function that describes a part shape in the spatial frequency domain is the Discrete Fourier Transform (DTF). Fourier series are often used in analysis of surface profiles, especially for surface roughness (Raja, 1977). Hence, it is used here to compare the shape fidelity of the sheet metal parts. For the sake of easy comparison, only a single 2-D cross section of each stamped part is mapped into the spatial-frequency domain for comparison of shape fidelity. The DTF for a measured 2-D profile $z(n)$ is given by

$$Z(m) = \sum_{n=0}^{N-1} z(n) \cdot e^{-j2\pi n(m/N)}; m = 0, 1, 2, \dots, N-1 \quad (1)$$

where:

m = frequency integer

n = sample integer and

N = number of samples.

$Z(m)$ is a complex array of DFT spectral coefficients for the N equally spaced frequencies. For an arbitrary spectral coefficient, say $Z(1) = a + bj$, the magnitude and phase can be calculated using the relations

$$|Z(1)| = \sqrt{a^2 + b^2} \quad \text{and} \quad \angle Z(1) = \tan^{-1} \left(\frac{b}{a} \right), \quad (2)$$

respectively. Samples of $z(n)$, i.e. z -axis elevations, are taken in the x -direction at a sampling interval of Δx . If the spatial representation of $z(n)$ is to be reconstructed from the frequency domain representation $Z(m)$, then the Inverse Discrete Fourier Transform (IDFT) must be used. This is given by

$$z(n) = \sum_{m=0}^{N-1} Z(m) \cdot e^{j2\pi n(m/N)}; n = 0, 1, 2, \dots, N-1. \quad (3)$$

In the 2-D case, the frequency f_m associated with a specific frequency integer m is equal to $m/(N \cdot \Delta x)$ and is expressed in

Table 1 Spectral coefficient magnitudes for the CAD shape and stamped parts

m	f_m (cycles/mm)	CAD Shape	CNC-Machined Die	PEL Die	Discrete Die
0	0.00	5619	5636	5645	5483
1	0.01	845	807	752	851
2	0.02	1246	1136	1145	953
3	0.04	475	442	459	335
4	0.05	170	185	196	142
5	0.06	82	68	99	42
6	0.07	58	37	47	19
7	0.08	32	13	30	21
8	0.10	41	40	42	24
9	0.11	35	40	38	20
10	0.12	9	20	21	12
11	0.13	14	10	17	10
12	0.14	8	9	13	8
13	0.16	8	6	12	6
14	0.17	6	5	9	6
15	0.18	12	9	3	5

cycles per unit distance. As seen in Fig. 10, when the magnitude $|Z(m)|$ and the phase $\angle Z(m)$ of the spectral coefficients are plotted against the frequency integer, they are symmetrical and inversely symmetrical about $m = 0$ (i.e., D.C. component of spectral representation), respectively. For this reason, the spectral coefficients up to $(N - 1)/2$ are all that is needed to completely describe the 2-D profiles' shape in the spatial frequency domain. Thus, the number of harmonics that are needed to reconstruct the 2-D shape is half the number of measured points.

As previously mentioned, each of the stamped benchmark parts shown (see Figs. 4b, 5b, and 6b) were measured along the darkened section line, as shown in Fig. 3, using a Coordinate Measuring Machine (CMM). For the PEL dies, this section line runs perpendicular to the lamination interfaces so that the effect of the straight bevel approximation is captured. A sampling interval of $\Delta x = 0.2$ mm was used for the 417 samples taken. Accordingly, spectral coefficients up to frequency integer $m = 208$ are all that is needed to represent the spatial frequency content of each part profile. In this case, the influence of spectral coefficient magnitudes, i.e., harmonics, above $m = 15$ are negligible. The frequency magnitude spectrum of the CAD profile and that of the measured profiles of each stamped part for up to $m = 15$ are listed in Table 1.

For any 2-D cross section of the measured part, the general shape of the cross-section is characterized by low frequency components. Accordingly, fine part details (e.g. small radii of curvature) are characterized by high frequency components. In the case of the sectional line on the benchmark part, the frequency components up to 0.048 cycles/mm for each stamped part are close in magnitude to the CAD shape. This simply

means that the general shape of each part is similar to that of the desired part shape. However, by comparing the higher frequency components (0.060 cycles/mm or $m = 5$ and above) of each part with the CAD shape in Fig. 3 shows how those of the discrete die part profile are consistently lower in magnitude than the others. This simply shows us how some of the part shape fidelity is lost when stamping with the discrete dies. At higher frequency components, $|Z(m)|$ for the PEL die part are generally higher than the CNC die part. This may be attributable to the sharp lamination interfaces that are transferred to the stamped part.

8 Comparison of the Fabrication Methods

In this section, comparisons are made between the three forming die fabrication methods based on the ten comparative study criterion. Even though the quantitative results of this section only pertain to a particular part shape and size, and set of forming conditions, the relative comparisons made between all three methods should be valid in most other situations. The reason for this is that this comparative study is based on the most common processes and practices used for sheet metal forming in industry. In many cases, it will simply be a case of linear scaling.

Time Required to Fabricate or Configure the Die. The time it takes to fabricate (CNC, PEL) or configure (discrete) a set of sheet metal forming dies directly impacts both the lead time and cost of tooling development. The actual times required to fabricate the forming dies using each of the candidate methods are summarized in Table 2. The downward trend in time needed for machining data extraction from the CAD model (CNC-machining, the most and discrete dies, the least) reflects the number of data points that each fabrication method uses to create the forming surface shape and also the degree of shape approximation. However, the actual times in an industrial setting will depend upon how optimized the data extraction computer software is and what additional software help modules are included (e.g. gouging check in CAM). Since PEL laminations are bevel cut along a 2-D profile, there is no problem with tool gouging because there is no cutting tool. Instead, the bevels are meant to be cut with a laser or AWJ cutter using "line-of-sight" CNC machining instructions (i.e., center point of cut + cutter orientation). The preparation time before the actual die shape can be machined or set is similar for CNC-machined and PEL dies but is negligible for discrete dies when automatic profiling is used. The time needed to machine or configure the die shape is greatest for CNC-machining and it will increase significantly for harder material (e.g. tool steel) as feedrates and spindle speeds have to be reduced. In addition, as the die size increases, time scaling of the rough cutting and finish cutting operations is roughly proportional to the volume of material

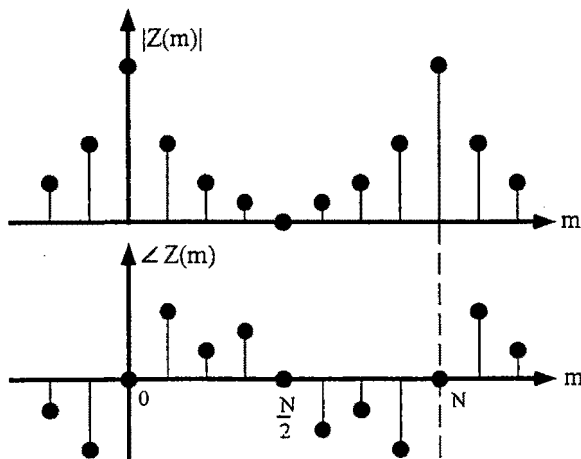


Fig. 10 Symmetrical nature about the DFT spectral coefficient's magnitude and phase

Table 2 Comparison of die fabrication/configuration times (hours)

	CNC Die	PEL Die	Discrete Die
Extraction of Machining or Configuration Data	1.0	0.5	0.3
Preparation before Die Shape is Machined or Configured	1.0	0.7	2.0 (setting shape with solid model) 0.0 (setting row by row)
Machining or Configuration of Die Shape	1.1	20.0 (weaving ball endmill) 0.6 (Flute-edge milling) 0.9 (AWJ) 0.5 (Nd:YAG Laser)	1.0 (setting shape with master model) 0.7 (setting row by row)
Grinding and Polishing Die Surface	2.0	1.5	0.2 (interpolator applied only)

removed and the area of the die's forming surface, respectively. In contrast, laser cutting PEL dies is essentially unaffected by material hardness. In fact, faster cutting rates can be achieved by increasing the power of the laser (Walczyk, 1996). The machining time is roughly proportional to the surface area of the die only. The only material removed is the narrow cut (kerf) made by the cutting method (e.g. laser) in the die lamination. Finally, the time required to grind and polish the rough die surface is similar for both the CNC-machining and PEL methods. The grinding time for CNC-machining will decrease significantly if 5-axis milling is used to make the finish cuts on the die surface. This is only true for die surfaces consisting of gentle curvatures. The equivalent operation for the discrete die method, i.e., applying an interpolator, takes only a fraction of the time that polishing and grinding of the PEL and CNC-machined die surfaces does.

Time Required to Reshape the Die's Forming Surface.

Assuming that many iterations are required to develop the correct die shape, the time required to reshape a die's forming surface will have an even greater impact, as compared with the initial fabrication time, on the cost and lead-time of a tooling development program. The results in Table 2 also apply in this case but with a few differences from the previous comparison (i.e., time required to fabricate or reconfigure the die). The main difference is that no preparation of the die(s) will be required before re-machining or reconfiguring the forming surface. In addition, the machining time for the CNC die will only be 1.0 hour since no roughing operation (0.1 hours) will be needed. For dies with deep draws that require more extensive rough cutting, the change in machining time would be greater. All conclusions drawn in the previous section also apply in this case.

Capital Cost of Machinery Used for Die Fabrication.

Although the capital investment in fabrication machinery is not directly added to the cost of tooling development in this study, it is an amortized expense that greatly influences the manufacturing company's choice of a die fabrication method. The two most important capabilities of any piece of fabrication machinery is the die size it can handle and how fast it can fabricate or configure a die.

A 3-axis CNC machining center was used to fabricate the CNC-machined dies. The maximum rate at which a solid die can be machined is dependent upon the material composition and it's hardness regardless of whether there is surplus spindle power available (Oberg, 1988). However, the maximum die size that can be handled is solely dependent upon the work area of the machining center. The cost of a 3-axis machine can be estimated, as a function of the work bed area, with a linear equation based on data collected from a major U.S. machine tool builder (Horner, 1995). The equation is as follows:

$$\text{Cost}(\$) = 80000 \cdot (\text{bed work area in m}^2) + 40000. \quad (4)$$

Similar equations can be developed for 4 and 5-axis CNC machining centers.

Assuming that a dedicated piece of equipment, called a Die Lamination Profiling (DLP) machine (see Walczyk, 1996),

fitted with a pulsed Nd:YAG laser cutter (fastest method identified) is used to fabricate the PEL dies, then the major capital cost item will be the laser. The maximum rate at which a PEL die can be fabricated is dependent upon the cutting speed of the laser. Since a laser's maximum cutting speed has been shown to be dependent on laser power (Walczyk, 1996), then the laser power is the limiting factor in fabrication rate. According to a major international laser manufacturer, the cost of various Nd:YAG lasers (including beam delivery system) with different output powers is listed in Table 3 (from Rofin-Sinar, Inc.). Fitting a linear equation to this data yields the following estimation formula for the laser price versus average maximum output power:

$$\text{Cost}(\$) = 150 \cdot (\text{Laser Power in Watts}) + 45000 \quad (5)$$

An estimated \$50,000 is added to the laser cost to cover the additional cost of a DLP machine. Since the cutting means are stationary with a DLP machine and only the laminations are moved, larger die sizes only require an enlargement of the machine's loading and receiving bins. This is a relatively inexpensive task compared to that of a CNC machining center. With CNC machining centers, expansion of the work bed area requires large stiff frames be used which quickly raises the machine's cost (as reflected in Eq. 4).

When using discrete dies, there are two major capital cost items: the profiling mechanism and the reconfigurable discrete die(s) itself. The cost for both of the high resolution dies used for the comparative study was \$20K. A good "rule-of-thumb" for estimating the cost of a discrete die is that it will scale roughly with the volume (or weight) of material (steel in this case) used in it's construction. Although a automatic profiling mechanism for setting the high-resolution discrete dies was not built for this study, it's cost is estimated to be around \$50K.

Cost of Raw Materials Used to Fabricate the Dies.

The term "raw materials" refers to those materials directly used in the construction of the dies. The expense of these raw materials figures directly into the total cost of die development. The CNC-machined dies were made out of two metal billets each being 670 cm³ of C11L17 steel. The price for this type of steel at the time of purchase was \$0.0227/cm³ so the total price for the billets was \$30. For both of the PEL dies, 138 laminations made out of relatively inexpensive cold-drawn AISI 1010 steel sheet were used. With a lamination size of 1.5 mm thick x 7.0 cm x 10.2 cm and 1010 steel at \$0.0132/cm³, the total cost for the material was \$19. The most inexpensive of all the methods were the discrete dies since the only raw materials required were two 0.8 mm thick x 10.2 cm x 10.2 cm pieces of 460 Elvax. Total cost for the Elvax was about \$0.20. The low Elvax

Table 3 Average output power versus base price for an Nd:YAG laser cutter

Laser Power (Watts)	Laser Peak Power (Watts)	Cost (\$)
300	5000	78K
500	10000	105K
1000	15000	184K

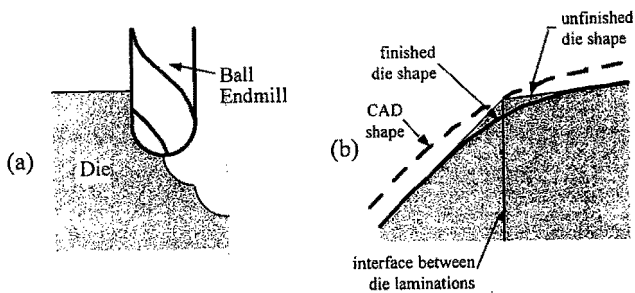


Fig. 11 (a) Scalped surface profile from conventional milling and (b) shape approximation of beveled profiled-edge laminations

cost may be misleading for large batches of parts formed with the discrete dies because an interpolator mask will only last for a relatively low number of stampings (compared to solid surface). In this case, it would be better to consider the interpolator as a consumable during forming.

Cost of Process Consumables Used During Die Fabrication. The cost of consumables used during the fabrication of the forming dies (e.g. cutting tools) also figures directly into the cost of the tooling development. While fabricating the CNC-machined dies, the total cost was \$57. For laser-cut PEL dies, the total cost of consumables, extrapolated from tests with lamination laser cutting, would be \$25. Aside from the electrical power used for setting the dies, there were no consumables used for the discrete dies. CNC-machining a forming die clearly has the highest cost for consumables mainly due to the cutting tools which are used on that die and no other. This is a typical practice in industry.

Shape Fidelity of Parts Formed with the Die Sets. The shape fidelity of a die-formed sheet metal part will be defined as how well the part faithfully reproduces the intended CAD part shape. As previously discussed, the spatial frequency content of a sheet metal part compared to its CAD shape is a good measure of its shape fidelity. According to shape measurement in the spatial frequency domain, the shape of the parts formed with the CNC-machined dies and the PEL dies are faithful to the CAD shape but not exact. With CNC-machining, the scalped die surface left by the surface machining operation, as shown in Fig. 11a, must be smoothed thereby introducing some approximation to the die shape. As discussed in the following reference, there is also geometric error introduced by the straight bevel approximation of the PEL die laminations as shown in Fig. 11b.

Of the three fabrication methods, stamping with discrete dies introduces the greatest loss in shape fidelity as previously discussed. Both the finite size of the die elements and the deformability of the interpolator contribute to this problem. The smallest details (e.g. corner radius) that can be formed into a part are directly affected by the size of the discrete die's elements. Ousterhout (1991) has pointed out that shape fidelity is also limited by the maximum wall slope or the minimum in-plane ($X-Y$ plane) radius that can be formed by a matrix of pins.

Limitations on Die Geometry Imposed by Fabrication Method. Each fabrication method imposes certain limitations on the allowable geometrical features of the die's forming surface. The more geometrical limitations imposed, the longer it will take to fabricate the die. Although CNC-machining is capable of creating very complex surfaces, the machinable die geometries are limited by the accessibility and size of the cutting tool ($\varnothing 6.4$ mm in this case). Concave features in the die with steep walls and internal radii are

limited by the tool spindle geometry and the ball endmill size, respectively. Long endmills must be used for machining deep cavities. Unfortunately, excessive deflection of a long endmill from cutting forces decreases the accuracy of the machining and increases the probability of the endmill breaking. The endmill can be shortened, but this decreases the cavity depth that can be machined into the die surface. The endmill diameter can be increased (i.e. stiffening the tool) but this limits the smallest radius of curvature (e.g. grooves and bend radii) of the die surface that can be machined. Undercuts in the die are not possible unless portions of the die are machined separately and then reassembled or if the complete die is reoriented and then reregistered. Both options will significantly increase the machining time.

There are far fewer limitations on die geometry with a PEL die fabricated by laser or AWJ cutting. Specifically, the PEL method avoids the tool accessibility problem and the geometry limitations imposed by a cutting tool. Since machining occurs in two dimensions only, (profiling a lamination's top edge), there is essentially no limitation on what profile can be machined. Even undercuts and backdrafts in the die are possible, although maybe not practical. Furthermore, unlike CNC-machining, the threat of gouging a lamination doesn't exist when machining PEL laminations since there are no cutting tools or check surfaces to deal with. There are, however, limitations to the maximum bevel angle that can be cut into the lamination (see Walczyk, 1996). Since there is no cutting tool used in the fabrication of a PEL die, the only geometry limitation imposed by the cutting means is the width of the kerf that is cut by the laser (≈ 0.1 mm) or the AWJ (≈ 0.7 mm). Another limitation on the die geometry is that the radius of curvatures in the $X-Z$ plane (across lamination widths) should not be any smaller than the lamination thickness (1.5 mm in this case).

There are also limitations on the die geometry with discrete dies. These type of dies most crudely approximate the intended die surface because of the element size and the interpolator thickness (≈ 0.8 mm in this case). Undercuts with discrete dies are not at all possible because a die element can only have one height. These limitations are less of an issue to fabrication time, as compared with CNC-machining and PEL methods, since the time to set a reconfigurable discrete die remains essentially constant regardless of the die shape.

Limitations on Forming Load. If the loads encountered during forming of a sheet metal part are too high for a particular die construction (i.e., solid CNC-machined, PEL, or discrete) to handle, then the part shape must be redesigned to yield lower forming loads. Unfortunately, a part redesign translates into a longer development time. For a solid CNC-machined die, the only limitation on forming loads is that contact stresses between the sheet metal part and the die during forming cannot exceed the compressive strength of the die material (234 MPa in for 11L17 steel). When this compressive strength is exceeded then permanent damage to the die surface will occur.

PEL and discrete dies have more limitations due to their non-continuous construction. For a PEL die, high contact stresses are also a problem ($\sigma_{yield} = 379$ MPa for SAE 1010 steel). More important is the fact that high transverse loads can cause excessive deflection in the clamped lamination array and inaccuracies in the die shape. Discrete dies are even more vulnerable to some sort of failure or loss of shape (i.e., pins slipping) from high forming loads. Furthermore, the interpolator can fail ($\sigma_{yield} = 18$ MPa for 460 Elvax) resulting in dimpling of the part. Discrete die pins also have the potential to bend elastically which results in a loss of die shape.

Limitations on Die Size. As part of a flexible manufacturing system, the die fabrication method used for tooling development should ideally impose no limitations on a die's size. The only size limits on CNC-machining of a die is the work volume

of the machining center used. Currently, there are very large gantry-style multi-axis machining centers available which are used for milling automotive body panel dies (Horner, 1995). A similar situation exists for PEL dies in that the only size restriction is the capacity of the DLP machine. Because of the stationary cutting means of the DLP machine design (see Walczyk, 1996), expanding the loading and receiving containers for larger die laminations is a relatively simple matter.

For discrete dies, the maximum size that a die can be is a function of the element size because of potential manufacturing tolerance build-up. For example, the width tolerances of 3.0 mm square steel stock available in the U.S. is typically +0.00/-0.05 mm. Although it's a statistically improbable situation, a 60 element high (18 cm), column has the potential to be 1 element width (3.0 mm) shorter than neighboring element columns if all the elements in the column are only 2.95 mm. This would be an unacceptable situation.

Limitations on Incorporating a Blankholder. The shape and configuration (e.g. flat holder, edge beads) of the blankholder is usually designed simultaneously with the forming die. How easily a blankholder is incorporated into the finished tooling is very important to reducing the time and cost of tooling development. The techniques for incorporating a blankholder in CNC-machined dies are well known. It is slightly more difficult with PEL dies because of the restrictions that the clamping/registration frame imposes. The most limitations on incorporating a blankholder are with discrete dies because of the massive die frame required, and the inability of the die elements to be used as an effective binding surface.

9 Summary and Conclusions

In this comparative study, all three of the candidate fabrication methods are compared to each other with regards to their performance in a flexible manufacturing system, particularly one that utilizes closed-loop process control principles in tooling development. The study first entailed designing and building a set of matched dies by CNC-machining solid billets, individually profiling laminations in an array, and setting a reconfigurable matrix of closely-packed pins (i.e., discrete die). The dies were used for stamping experiments of a benchmark sheet metal part.

The following discussion generalizes about the three fabrication methods based on cost and lead-time comparisons. Fabricating a PEL die and setting a discrete die is generally faster than CNC-machining a die of similar size, especially if harder die materials (e.g. tool steel) are involved. The current capital cost of CNC fabrication equipment (i.e. machining centers) is less than that of a laser-based DLP machine due to the cost of the laser. However, expanding the size of a DLP machine should be less expensive. From an estimated cost analysis, costs of discrete die machinery, i.e. reconfigurable dies and setting equipment, are similar to that of CNC machinery. Of the three fabrication methods, the costs of raw materials and process consumables are lowest for discrete dies because of their reconfigurable and universal nature.

Comparisons based on the shape resolution and flexibility can also be used to generalize about the three fabrication methods. Compared to CNC-machined and PEL dies, discrete dies, with their discretized forming surfaces, yield parts with the worst shape fidelity. Die geometry is limited with CNC-machining because of tooling accessibility problems and the size of the cutting tool. This is not the case with PEL dies since the laser or AWJ-cut kerf is very narrow and individual laminations are machined in 2-D only. Regarding limitations to the forming force, discrete dies are vulnerable to interpolator failure, pin slippage from high forming loads, and pin bending. These types of die failures can be minimized or eliminated by the proper choice of clamping method, pin size and interpolator material.

The only major limitation with CNC-machined and PEL dies is the compressive strength of the die material. The discrete die method is the only one of the three with limitations on die size. The size of a discrete die is a function of constituent pins in that when the pin size increases, so to does the maximum achievable die size. Unfortunately the discretization of the forming surface also becomes coarser. Finally, the only method that imposes significant limitations on the blankholder configuration are discrete dies.

From these comparative study results, some general conclusions about all three fabrication methods involved can be formulated. Generally, the PEL die method is very similar to CNC-machining a billet with regards to most of the comparison criteria. However, a PEL die construction eliminates most tooling accessibility problems, reduces limitations on the die geometry and allows for faster fabrication because laser cutting (and AWJ to some degree) is not dependent upon material hardness. CNC-machining a billet is better than a PEL die construction in a situation where a completely solid die is not needed (e.g. rapid temperature rise of die preferred for hot forming). In this situation, it is easier to decrease the die's thermal mass by CNC machining. Compared with both of these fabrication methods, there are limits on part shape fidelity, maximum forming loads, die geometry, and blankholder incorporation with a discrete die construction. However, discrete dies excel in terms of cost and fabrication time. This particular combination of process characteristics is ideal when many different types of gently-curving parts need to be formed in small lot sizes. This is oftentimes the situation in the aerospace and defense industries.

By comparing them with the current rapid, low-cost fabrication method used in industry, i.e. CNC-machining a solid billet, both the PEL die and discrete die methods are also shown to be rapid, low-cost and, most importantly, worthy of industrial implementation. Rapid tooling methods, including the three candidate fabrication methods, are seeing increased usage in industry by those who need better ways to develop and bring their sheet metal products to market in ways that are quicker and more economical than ever before. Layer manufacturing, i.e. rapid prototyping, methods are what is driving this increased popularity. Unfortunately these methods are not yet well suited for high-production sheet metal forming dies where high strength, toughness, and smooth surface finishes are required (Aubin, 1994). This makes a strong case to the sheet metal forming sector of industry to significantly advance the state-of-the-art for both PEL and discrete sheet metal forming dies.

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