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Rapid Prototyping of Extrusion Dies Using Layer-Based Techniques

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Extrusion die design and development often requires significant craftsman skill and iterative improvement to arrive at a production-ready die geometry. Constructing the dies used during this iterative process from layers, rather than from one solid block of material, offers unique opportunities to improve die development efficiency when coupled with concepts drawn from the rapid prototyping field. This article presents a proof-of-concept illustrating the potential utility of layer-based extrusion dies for the die design and fabrication process. The major benefits include greater flexibility in the design process, a more efficient, automated fabrication technique, and a means for performing localized die modifications and repairs.

Keywords computer-aided design, extrusion die design, layered manufacturing, rapid prototyping

1. Introduction

Rapid prototyping (RP) describes a broad range of technologies and methodologies for the efficient manufacturing of mechanical components. While little more than a research curiosity a decade ago, hundreds of commercial RP systems are now deployed around the world in leading corporations involved in design and manufacturing. Case studies report time and cost savings of 30 to 95%, with 50% quite common, when contrasting RP techniques with conventional fabrication methods (Ref 1). In design, fast conversion of concepts into tangible engineering prototypes enables and encourages iterative product improvement. In manufacturing, low-volume end use components and tooling for higher-volume material-conversion processes can be quickly generated. The latter is often referred to as rapid tooling.

Many of the techniques developed for RP are applicable to extrusion die design and fabrication, and similar efficiency benefits are anticipated. Despite the emergence of increasingly powerful numerical codes for metal deformation simulation (Ref 2, 3) iteration on real or physical model materials remains central to most extrusion die development (Ref 4-6). This is especially critical during the development of extrusion dies with complex cross sections, which are being investigated to control material flow and develop certain mechanical properties as well as surface finish (Ref 7). Applying RP concepts to create prototype dies for model material extrusion will improve efficiency by increasing the number of iterations possible during the important early stages of die development. These same concepts may be extended for manufacturing prototype or end-use dies for real product extrusion. Others have demonstrated utility in applications including polyurethane molding (Ref 8) and pressure die-casting (Ref 9).

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This article reviews the relevant RP fundamentals and illustrates the power of the layerwise manufacturing technique commonly applied by these processes. Extrusion die design, particularly for complex geometries as are currently being investigated, is discussed. Creating dies from discrete layers, as proposed in the 1950s for other metalforming applications (Ref 10), is applied for extrusion dies, and preliminary experimental results are presented. This article concludes by examining strengths and weaknesses of this approach for extrusion while outlining potential applications.

2. Rapid Prototyping

Rapid prototyping is defined as the rapid production of prototype models (Ref 11). Many commercial RP processes and industrial success stories have emerged in the last decade. Rapid prototyping represents both a methodology and group of technologies that have proven particularly effective at speeding the conversion of design information into physical reality. In general, this is achieved by standardizing the information required by manufacturing processes while automating the manner in which this defining information is processed. This automation is possible, in part, due to the development of a group of manufacturing processes with simplified information requirements. These are known synonymously as solid freeform fabrication (SFF) or solid freeform manufacturing (SFM) processes.

2.1 Solid Freeform Fabrication/Solid Freeform Manufacturing

Solid freeform fabrication or SFM processes have received substantial attention and are responsible for much of the recent growth in the application of RP. The key feature of any process classified as an SFF process is that it requires no part-specific tooling or human intervention to realize components (Ref 12). The attempts to satisfy this goal have stimulated the development of many processes with greatly simplified informational requirements, and this facilitates a more automatic push-button method for component manufacture. Many SFF processes, for example, make use of layered manufacturing techniques (LMTs) which ultimately require only planar information, rather than three-dimensional information, to control process hardware.

2.2 Layered Manufacturing Techniques

Solid components are created using LMTs by additively building up planar material layers corresponding to component cross sections. Layer-based techniques were proposed in the 1950s for making hydroforming tooling (Ref 10), and they have been studied more recently for other tooling applications (Ref 8, 9, 13, 14). Layer-based techniques have also proven quite useful in the context of RP, specifically given the tool and operator independence goals of SFF.

Interest in using LMTs for prototype components began with nonstructural materials such as paper, wax, and plastic; however, metal, ceramic, and composite components are now being produced using these techniques. Most RP processes based on LMTs utilize raw material layers on the order of hundreds of microns (several thousandths of an inch) to construct components. These techniques benefit from being able to create components of nearly unrestricted shape. Most processes are self-fixturing, and by constructing parts from thin layers, tool accessibility limitations common during machining are not experienced. Special case fixturing and tool path planning are rarely a consideration or obstacle to productivity when using these processes. Additionally, using such thin layers allows each contour of the layers comprising the part to be cut without regard to variability in the slope of the layer around its periphery. This further simplifies the information necessary to drive the layer-based process. Unfortunately, fabricating components using very thin layers is not without drawbacks. The number of layers required to form a typical part is large and the time required to process each layer can be significant. Approximations using edges perpendicular to each layer are common and produce spatial aliasing, also known as stair stepping, which is undesirable in certain situations.

Some applications using much thicker layers have been reported. Ford Motor Company used LMTs to produce a prototype engine block using numerically controlled (NC) machined 1 in. thick steel layers bonded using a special diffusion bonding operation (Ref 15). This eliminates many tool accessibility difficulties of machining components with complex internal passages and deep pockets, while retaining many of the benefits associated with time-tested machining such as the ability to machine a wide variety of materials, achieve high tolerances, and control surface finish. Many trade-offs between material thickness, manufacturing process, and target material must certainly be considered when selecting an appropriate LMT process.

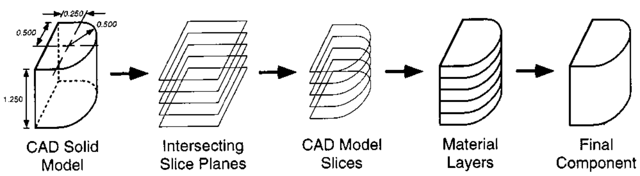

Fig. 1 Layered manufacturing techniques (Ref 16)

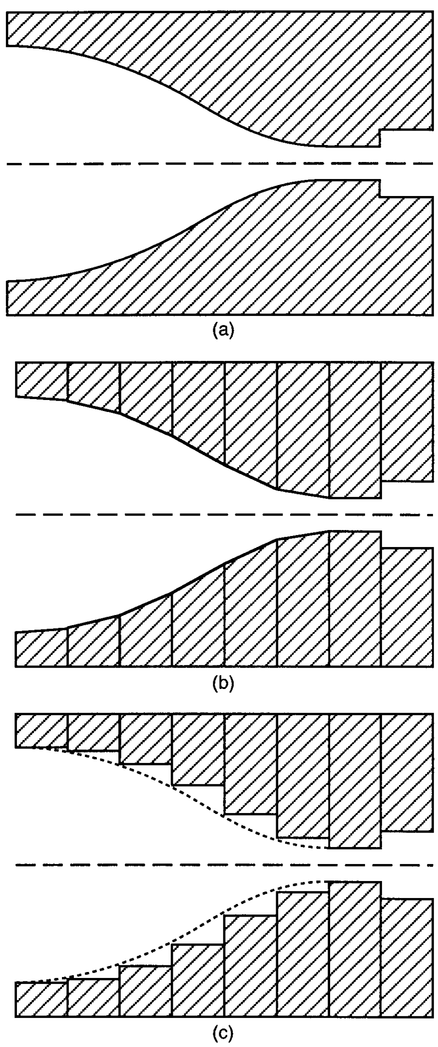

Fig. 2 Extrusion die cross sections. (a) Conventional. (b) Contoured edge layered die. (c) Perpendicular edge layered die

2.3 Driving Information

The power of LMTs and RP in general stems from the ability to quickly transform a geometrically complex three-dimensional design into the low-level control instructions necessary to guide an information-driven manufacturing process. Computer-aided design (CAD) solid models, which are computer-sensible representations of three-dimensional objects, are generally required to drive RP systems. Figure 1 illustrates how a CAD solid model is intersected to create slices corresponding to various layers comprising a final component. Note that while this example shape is quite simple for illustrative purposes, solid models representing more complex three-dimensional objects can be processed equally well using this technique. Increased geometric complexity will make the power of solid modeling fully evident.

The key requirement that has prevented some from enjoying the benefits of LMT is that three-dimensional solid models, rather than two-dimensional CAD or manual drawings, are required to efficiently drive these processes. However, improvements in desktop computing power, combined with the introduction of many new solid modeling packages, have today made three-dimensional CAD solid modeling capability accessible to even the smallest firms.

3. Layered Extrusion Dies

Constructing extrusion dies using discrete material layers offers many benefits similar to those realized for other applications of LMT (Ref 9). While envisioned principally as a tool to expedite the design and iterative refinement of extrusion dies, the proposed use of layered extrusion dies may also be applicable in production situations. This is an especially attractive approach for short production runs, where building a die using traditional methods would be economically prohibitive.

3.1 Die Development

Despite advancements in the die design and fabrication process, highly complex tooling is usually not perfected in one design iteration. It is quite often necessary to go through several trial and error iterations to introduce needed corrections into the die geometry. A major limitation of this approach is that these corrections are often performed manually and the original design is very seldom updated. Consequently, these modifications and the associated process knowledge are not easily captured and incorporated into future designs, and the general state of practice does not advance. This situation is exacerbated, and turnaround times can be lengthened substantially, when the die is manufactured outside of the extrusion plant. The LMT approach allows us to capture the necessary changes and easily incorporate them in all new designs.

3.2 Die Styles

Figure 2 contrasts a typical solid extrusion die and two forms of layered extrusion dies. The conventional die cross section shown in Fig. 2(a) illustrates a very smooth interior die surface, fabricated from a single piece of wrought stock. The layered extrusion die termed a *contoured edge layered die* shown in Fig. 2(b) offers a close approximation to this smooth, solid die. The smooth contour is approximated here by layers with straight edges around their periphery.

The layered extrusion die termed a *perpendicular edge layered die* offers an even simpler alternative. As shown in Fig. 2(c), this type of die approximates a smooth die contour using discrete layers with edges perpendicular to each layer about the periphery of each contour. Although this provides a poorer approximation to a smooth contour, the approximation offered by this die style is generally sufficient for the target application of extrusion. Localized dead metal zones will form in the corners created by the discrete die layers and serve to effectively smooth the die surface. Regardless of the type of approximation used, layered extrusion dies offer an attractive alternative to dies fabricated from one solid piece of material.

3.3 Die Fabrication

Contoured edge layered dies and perpendicular edge layered dies can be machined from planar stock. Both die styles can be cut using a three-axis NC machining center; however, the former is more efficiently cut using a five-axis mill to avoid requiring multiple fine passes to create sloped edges. Layer edges are best machined using the sides of an end mill. Figures 2(b) and (c) illustrate dies made from uniformly thick material layers, and this facilitates process standardization—in terms of stock material inventory, handling, fixturing, and tool path planning. However, it is possible to create a die using layers of varying thickness. In either case, a minimum layer thickness will be required for machining without complicated part fixturing.

Both die styles require planar contour information to define their shape. Perpendicular edge layered dies only require a single contour corresponding to the shape of each constituent layer; however, two contours are required to define the shape of each contoured edge layered die. Interpolation between these two contours can be used to determine the cut angle as a function of location about each pair of contours. If these dies are to be constructed of n layers, then either n or $n + 1$ contours, respectively, are required to fully define all die layers since mating faces of the contoured edge layered die will have identical contours. Contours representing a die design can be manually created, but additional advantages of layered dies will be realized when a CAD solid model is intersected by slice planes and the resulting slices used to automatically guide die layer machining. This is illustrated by Fig. 3.

Computer-aided design solid models are routinely transferred to RP systems using a polygonal approximate representation. Known as STL, this approximation can also be used in this application, and previous capability has been developed

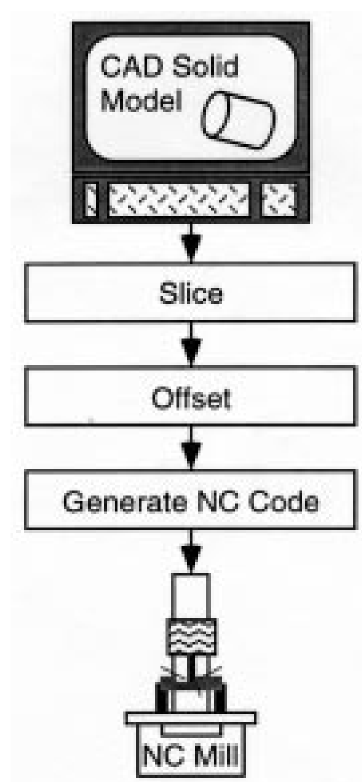

Fig. 3 Architecture for creating layered dies from CAD solid models

to slice these files (Ref 17). Slice contours must be offset to account for the cutter radius, and instructions that guide the NC milling machine, known as “NC code,” must be generated.

Provisions must be made to ensure proper alignment between successive die layers. A number of options such as interlocking features, keyways, or alignment pins can be used. Alignment pins provide an easy alternative since holes to accommodate each pin can be machined in each die layer while it is fixtured for edge profile cutting. This will lead to a high degree of alignment accuracy while being reasonably automated. A simple scheme for layer assemblage and alignment also will facilitate die modifications and maintenance.

3.4 Die Modifications

By constructing extrusion dies from discrete layers, localized die geometry changes can be made without having to manufacture an entirely new die. Figure 4 shows die contour half cross sections similar to those of Fig. 2. The dark regions illustrate the portion of each die that must be modified to realize a revised die geometry as shown in Fig. 4.

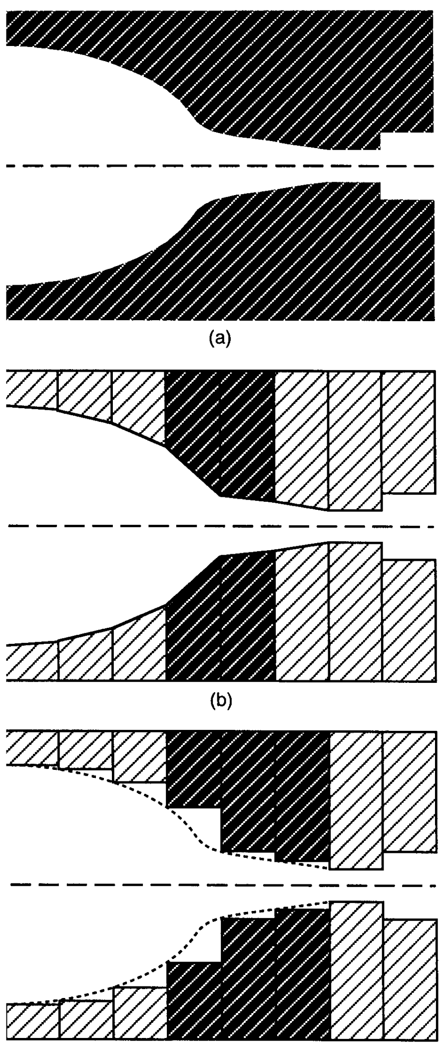

Fig. 4 Selective die layer substitution example

If a solid die is used as illustrated by Fig. 4(a), in some cases it may be possible to recut the existing die if the shape change is purely subtractive and the location is easily accessible, but often the new die geometry must be cut from an entirely new piece of stock to realize the revised geometry. The profile change is less costly when layered dies as shown in Fig. 4(b) and (c) are used because only select layers of each die need to be altered. While saving material, the most important savings are the time and personnel required to effect the modification.

3.5 Potential Limitations

Although there are many potential benefits of using layered extrusion dies, their application is not without limitations. Flexural strength may be limited if unbonded die layers are used. This is particularly relevant for layers near the extrusion orifice. This may place lower bounds on the thickness or material properties selected for die layers. It is critical to calculate the die deflection during extrusion and compensate for it in the die design stage. This deflection can be responsible for a lack of performance in terms of achieving the required geometrical tolerances. Problems with die layer deflection and material ingress in layer-based tooling have been comprehensively discussed in the literature by Soar and Dickens (Ref 9).

Complex dies that produce hollow product by using mandrels may not be well suited for unbonded LMT application. If

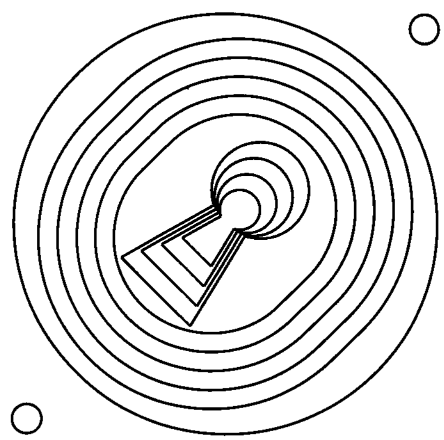

Fig. 5 Die stack for initial die design

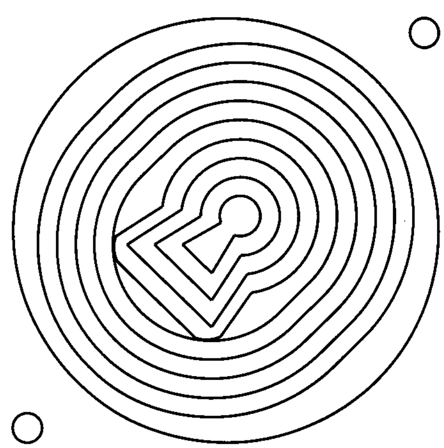

Fig. 6 Die stack for improved die design

these techniques are to be used, it may be necessary to employ conventionally manufactured mandrels and bridges, unless it is possible to realize these components using thick layers stacked into the die.

None of these problems appear to be insurmountable or make the further exploration of layered extrusion dies unfavorable.

4. Experimental Results and Discussion

A series of preliminary experiments were carried out to evaluate the merit of the proposed technique. A key blank shape similar in geometry to the work of Ref 18 was used for the extrusion as a compromise between the complex shapes used in industry and the simpler shapes required for basic research. Initial experiments were conducted on plastic dies useful for model material extrusion. Plasticine was used as a modeling material, as the nature of its flow at room temperature is quite similar to that of aluminum at hot extrusion temperatures. This physical modeling technique has been applied successfully to metal flow analysis in various metalforming processes and detailed description of this technique applied to extrusion is given by Prats and Misiolek (Ref 4).

4.1 Die Configurations

The die design was done for the keyhole shape presented in Fig. 5 to 7. The layers were designed as perpendicular edge layers, and all layers were standardized at a thickness of 6.35 mm (0.250 in.) to avoid the complexity of acquiring and managing material of multiple thicknesses.

Two die configurations for the same extruded shape were designed to highlight the utility of the layered extrusion die concept. These are shown in Fig. 5 and 6. Of the nine layers comprising each die, all but three layers are the same in both dies. Consequently, only a total of twelve layers had to be manufactured. The layers that were identical in both designs were shared, and the three different layers were exchanged to form two unique die geometries. Additionally, by removing select layers it was possible to further alter die shape without requiring the creation of any new die hardware. This affords great flexibility and significantly enhances the efficiency of the trial-and-error die development process.

4.2 Die Fabrication and Experimental Setup

Machining of the dies was performed on a relatively inexpensive benchtop NC milling machine. The NC code was generated directly from the CAD drawings via CAM software. Figure 8 shows the assemblage of die layers used for an extrusion trial. Two pins, with a press fit clearance to holes in each die layer, were used to ensure proper alignment between all die layers. A backer plate of 0.500 in. thickness, not shown here, was used to prevent excessive deflection or fracture of the die layer containing the extrusion orifice. This die stack was centered on the press using an annular ring with an insert that mates with the press container. The insert has two holes to accept the die layer alignment pins. This entire assemblage was mounted to the press with a bolster plate and four bolts.

4.3 Material Flow

Plasticine with a grid pattern imprinted on a center parting surface of the billet was used for all extrusion trials. After extrusion, the plasticine was removed from the press container, and the die layers were separated one by one from the extrudate remaining in the deformation zone of the die. Flow analyses information can be extracted in two manners: by placing an initial grid on the interior of the billet prior to deformation, and by extruding multilayered, multicolored billets. Both of these tech-

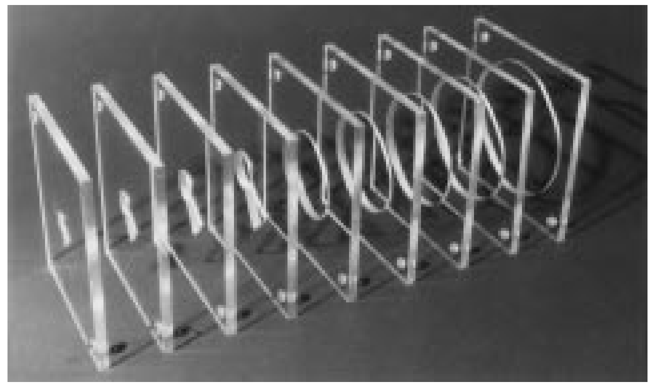

Fig. 7 Series of layers comprising a layered die

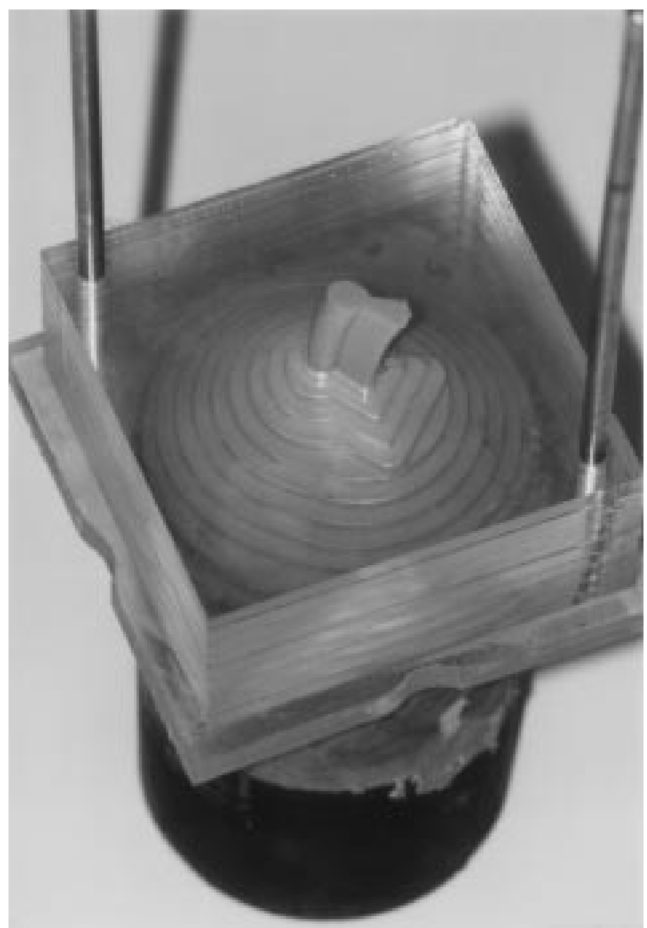

Fig. 8 Layered die stack, billet, and dummy block with extruded profile

niques have been used successfully in past material flow studies (Ref 4, 19). The evolution of the material flow is evident in the deformation of the grid pattern lines. The change of deformation zone geometry can be monitored in more than one plane depending on the shape of the extruded profile. The grid is photographed and then scanned into the computer for storage and image analysis. However, whereas observation of such deformations has historically been subjective, a proprietary image analysis software package developed in the Institute for Metal Forming at Lehigh University has been employed to accurately quantify this flow.

The flow pattern in Fig. 9 shows that the center of material flow is shifted toward the circular part of the key blank in the first die. This nonuniformity of the material flow will cause the extrudate to bend as it is being extruded and will require an additional stretching and straightening operation. It can possibly lead to some microstructural inhomogeneity resulting in surface defects along the thin section of the key blank and introduce gradients in mechanical properties along its cross section. The deformation pattern in Fig. 10 shows that the flow has been corrected towards the center of the part, which will result in a more uniform material flow and therefore straight extrudates with more homogenous microstructure in the final product. If a solid, one-piece die is used, any correction from the initial design (Fig. 9) would require extensive remachining or even machining of a new die. Using the LMT die, this transition simply requires a design modification and replacement of three die layers as presented in the above example.

To create the die in Fig. 11, no extra die components had to be machined. The existing layers of the improved die (Fig. 6) were reassembled, with only alternate layers included. This produced a shallower die—increasing the half-angle of the die. The result of this is the flow pattern presented in Fig. 12. This pattern shows even more improvement on the metal flow, with a very regular and uniform motion through the center of the die orifice.

The detail in Fig. 12 illustrates how the formation of the dead metal zone in the corners of the perpendicular edge dies does effectively smooth out the profile. The shear zone produced along the dead metal zone creates a smooth surface as in the conventional die design. This approach is used in everyday practice in aluminum extrusion technology. The feeder plates, also known as weld plates, are used in front of the die allowing aluminum to create its own "tool" based on the plate geometry. They are usually plates around 1 in. thick with walls in a 90° angle to the die surface. The concept of multilayer die has been explored for different purposes. Misiolek and Zasadzinski (Ref 20, 21) proposed their extrudability testing die, which is built as a two-layered tool. This approach has been implemented in commercial practice where material flow is controlled by the geometry of the step die (Ref 22).

It is necessary to develop a set of inspection methods allowing quantitative description of the extrusion product quality. Among physical properties of great interest to extrusion manufacturers and users are straightness, geometrical tolerances of the cross section, surface quality (finish), and mechanical properties. Inspection and analysis of the extrudate quality needs to be expanded into analysis of the extrusion process itself. It is possible to quantify product defects and feed this information into a process model. This type approach has been proposed by Zasadzinski, Richert, and Misiolek (Ref 18) and applied to the control of the curvature of an extruded copper profile. In the

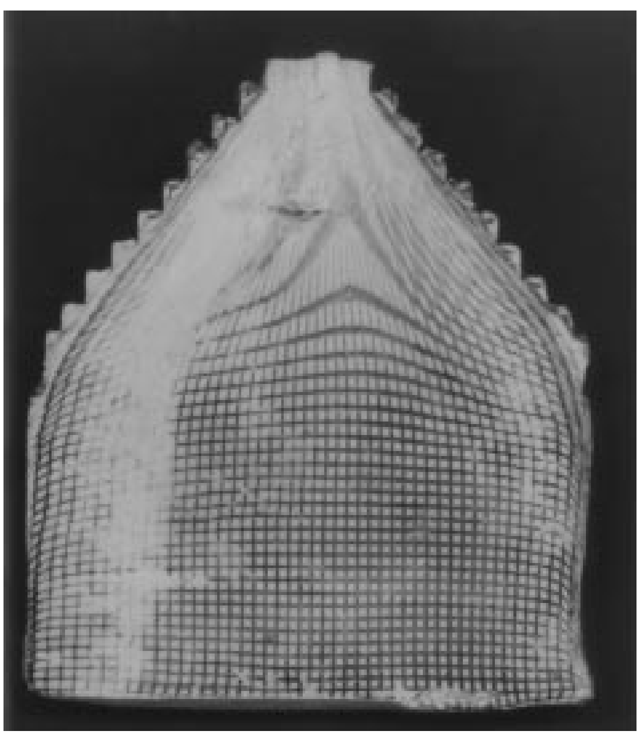

Fig. 9 Plasticine deformation flow results for initial die design (of Fig. 5)

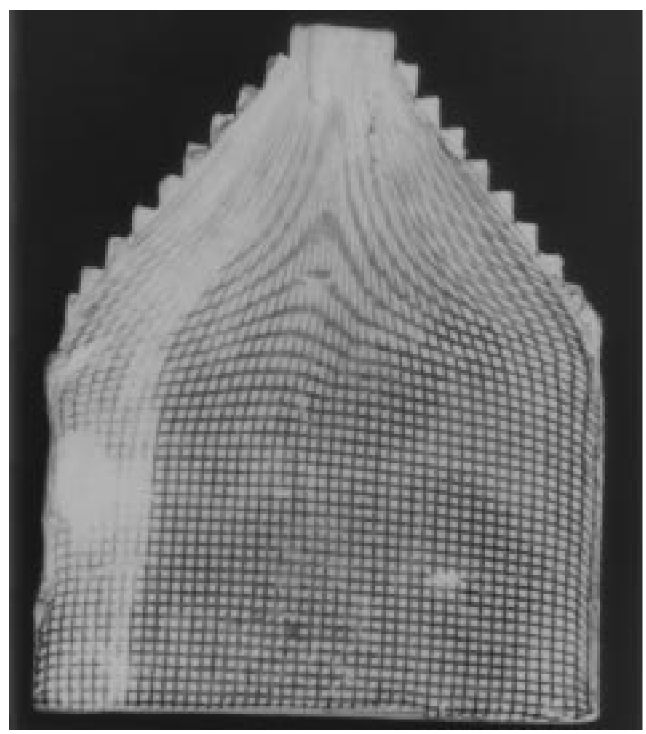

Fig. 10 Plasticine deformation flow results for improved die design (of Fig. 6)

proposed method, quantified extrudate curvature was fed back into the extrusion die design process. This allowed development of an algorithm that introduced necessary corrections in die design resulting in straight extrusion. Similar methods need to be developed for the process adjustments in order to improve desired product parameters. Further improvements in understanding of microstructure development during deformation are an example of necessary studies. Research on microstructure response to the extrusion process conditions reported recently (Ref 5, 23) is an example of studies in this direction that can benefit from LMT-based extrusion die development.

5. Conclusions

The concept of building a layered extrusion die using RP techniques has been successfully tested with a modeling material. Some of the major applications and benefits of this technique are:

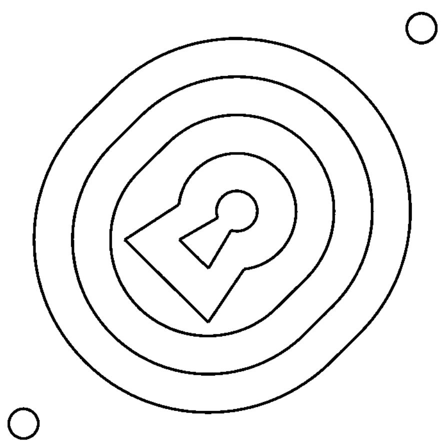

Fig. 11 Modified die design

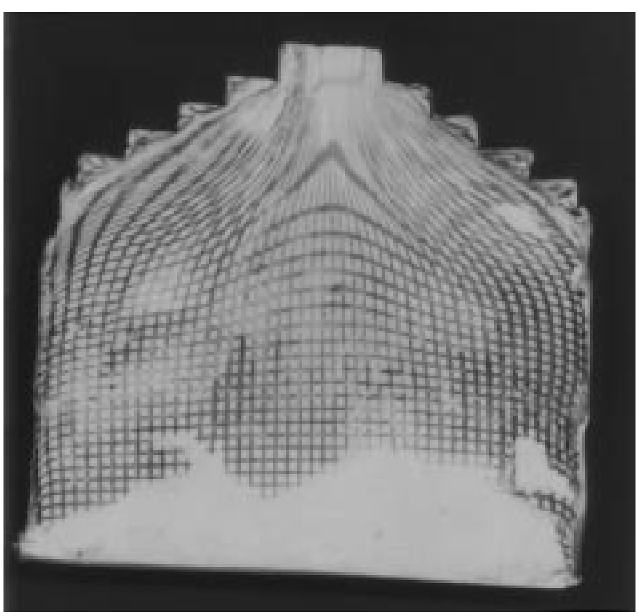

Fig. 12 Representative material flow pattern

- This proof-of-concept shows that this technique allows more flexible die development and design.
- This layered construction technique allows localized replacement of die layers, avoiding complete remanufacture of dies due to either die geometry changes or tool wear. The use of layers affords an opportunity to quickly/efficiently modify the die by selectively removing or reconfiguring of die layers.
- Stairstepping in perpendicular edge layer dies is not detrimental in extrusion due to dead material zone formation. However, results of previous studies on optimal die geometry need to be considered.
- Information on material flow can be fed back through the design process and changes in die design can be affected much more rapidly than with conventional monolithic dies.
- Use of layers provides for a systematic, automated manufacturing technique using few different stock pieces, few different machining techniques and tools, and little manual path planning.
- Increased die strength and tool life can be achieved by bonding of individual layers through diffusion bonding or mechanical joining and through use of different materials for individual layers.
- More efficient and rapid manufacturing techniques such as abrasive water jet cutting or laser cutting may easily be applied to machining each individual layer using this manufacturing process.
- In modeling material studies, the use of layers makes it easier to remove the unextruded part of the plasticine billet from the die.

The LMT tooling concept can be successfully applied to the extrusion of various materials. There are additional areas where further improvement can be gained. For example, conformal channels for temperature control can be easily applied leading to very successful, but so far, time consuming, solutions in terms of increased productivity of aluminum alloys that are hard to deform. Further research in this direction is recommended.

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