PROTOTYPING

Click on any of the titles below to jump to that section

Click Here to Close This Chapter

PROTOTYPING

Sometimes it will be necessary to produce prototype zinc alloy castings before committing to production tooling. This is because the manufacture of pressure die casting dies usually entails high cost and long lead-times that can delay normal product development schedules. Thus it is usual to use cheaper and lower lead-time methods of manufacture in order to produce prototypes that approximate the desired features of the proposed pressure diecasting.

The following factors must be considered when selecting an alternate process for prototyping a pressure die-cast product.

1. Details of the product application, such as operating environment and method of attachment
2. Performance specifications for the end product
3. Test schedule for the prototypes
4. Number of prototypes required
5. Cost and delivery schedule for the prototypes
6. Characteristics of the end product that must be matched by the prototype, including:
    - Shape and fit
    - Appearance, usually surface finish and treatment
    - Chemical properties, which affect atmospheric corrosion, galvanic corrosion and toxicity
    - Assembly requirements
    - Physical properties, such as density, electrical conductivity and thermal conductivity
    - Mechanical properties, such as tensile strength, ductility, hardness, wear resistance, and impact strength.

Where only a few prototypes are required the problem is not great. A method can usually be found which will produce a reasonable facsimile. This is especially so when only the shape of the part is important. When strength, or other intrinsic properties are to be tested, then more care has to be exercised in choosing the prototyping method. The rapid freezing conditions which pressure die castings undergo can lead to substantially different properties to those shown by an identical alloy cast by other methods. This is especially marked for the 4% aluminium alloys (# 2,3,5,7). If it proves impossible to match all the properties required then tooling suitable for making pressure die castings may have to be used for prototyping. This is also likely to be the case where an extended run of pre-production parts is required.

The following sections firstly detail the alternative methods of producing prototype components and the characteristics which each method imparts to the component and secondly review methods of rapid manufacture of pressure diecasting tools.

Click Here to Close This Chapter

Machining from Solid

Machining will produce a part that is dimensionally accurate and of good surface finish. The mechanical properties of the component will depend on the stock from which the part has been cut.

Ingot

The mechanical properties of components cut from casting alloy ingots will be different to those of pressure die cast material. The slow cooling rate in the ingot results in lower strength and ductility for the 4% alloys and to a lesser extent also ZA-8. Segregation can occur in ingots of ZA-12 and ZA-27 which will again result in unrepresentative properties.

Continuously cast bar

Where available, continuously cast alloy bar provides a feedstock which has tensile strength, yield strength and hardness values close to that of the pressure diecast alloy. These properties are homogenous and consistent. The close match allows prototypes to be made from the same alloy as the diecast end product. The limitation on use is the feedstock size. Commercial alloys are available up to 230mm diameter and rectangular and other shapes are also available.

Existing pressure castings

Prototypes can sometimes be made by altering castings of similar size and shape, or by cutting small components from large pressure die castings. Care must be taken to ensure that critical areas of the prototype are made from sound material that does not contain excessive defects. In particular, it should be noted that machining down a heavy section will remove the dense surface skin and can result in a component that is made entirely of the porous centre-line material. This will result in poor properties that are less than those which will be attained in the ultimate pressure casting.

For the 4% aluminium alloys, even if defective material is avoided, the “thinned down” component will not be quite as strong as the die cast end product. This is because strength varies with the original casting thickness (Figure 1).

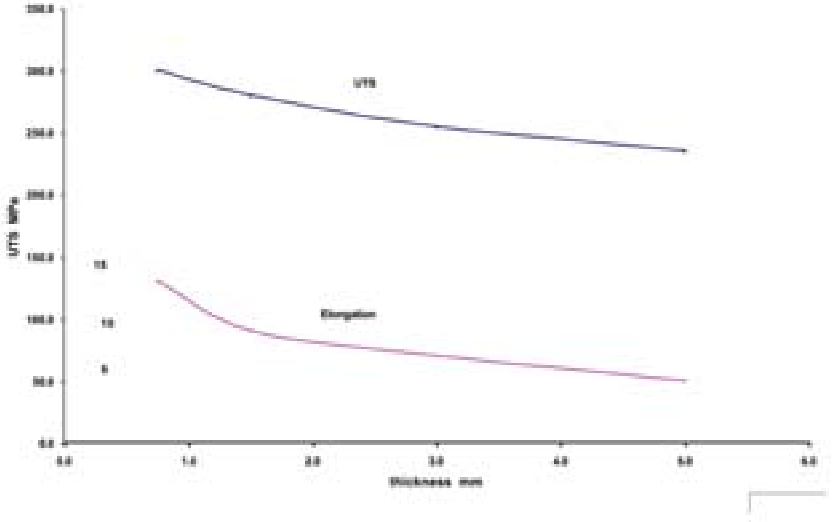

Figure 1. *Effect of casting thickness on the mechanical properties of Alloy 3.*

Click Here to Close This Chapter

The removal of the cast surface will expose subsurface porosity that can cause problems when painting and electroplating the prototypes.

Gravity Casting

In this section the term gravity casting means all non-high pressure methods of casting. The features which distinguish gravity from pressure die castings are:

- reduced dimensional accuracy
- greater minimum wall thickness
- generally a rougher surface finish
- slower cooling rate which decreases strength

The problem of reduced strength can be tackled by using a different alloy to that from which the pressure casting will be made. Gravity cast alloy ZA-12 has similar strength to pressure diecast alloys 3,5 and 7 and is widely used as a prototyping material for these alloys.

Most cast prototypes are made in disposable molds, eg sand molds. This means that the first step in producing a prototype is the manufacture of a pattern around which the mold is then formed.

Pattern making

As only a few components are usually required, the pattern does not have to be particularly durable and a variety of methods may be feasible.

Where the project involves substitution of an existing part, the original can be used as the pattern. In some cases this may involve segmenting the original in order to allow extraction after mold making, thinning wall sections or filling out features which cannot be satisfactorily cast (Figure 2).

Models of components may be used as patterns. These mock-ups can be in a variety of materials ranging from machined steel to glued paper. In the past, models have been cut using traditional machining methods and in many cases a fair amount of hand crafting. Recent developments in computer-based techniques have revolutionised this aspect of rapid prototyping (and is now extending into rapid tooling).

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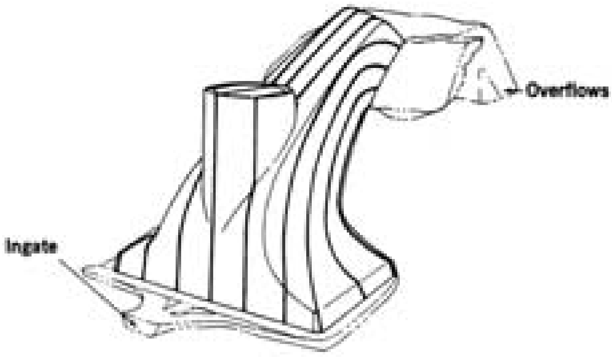

Figure 2. *Method of dividing water faucet casting into segments.*

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Rapid prototyping

The essential feature of all the techniques is that the component CAD file is used to generate a layer-by-layer build up of the model. The original CAD file may need extending by the prototyper to ensure that satisfactory support structures backing the functional surfaces are formed. The techniques differ in the method used to form the layer and in the materials in which the model can be made. The layering process does result in "stepping" on sloping surfaces which means a finishing operation might be required. Brief descriptions of the methods are given below. This is a rapidly advancing area in which comparisons can become out of date so Table 1 (which compares techniques) should be treated as being indicative only.

Stereo Lithography

A UV laser traces the slice pattern across the surface of a vat of photo-curable polymer thereby forming a thin solid shape. The worktable then lowers to allow a film of polymer to cover the slice and the process is repeated. When the full model is completed the uncured polymer drains away as it is removed from the vat. The model may be used as a conventional pattern or can be invested and then burnt away to make a precision casting mold.

The time taken to generate a model depends on its height. The projected area, or the making of a number of parts at the same time, has less effect on the time taken. Minimum slice thickness is around 0.1mm in epoxy resin and 0.05mm in acrylic resin.

Solid ground curing

The CAD slice is photocopied onto a glass photomat. UV light is then shone through this stencil onto a resin bath. Where the light falls the resin surface is immediately cured. Uncured resin is removed and replaced with supporting wax. The surface is machined flat, flooded with resin and the process repeated.

Selective laser sintering

In this method a CO2 laser is used to fuse powdered material together. The material may be plastic, metal or ceramic powder. After each slice is created, a roller spreads another thin layer of powder. On removal, the unsintered powder drains away. The models can be used as conventional patterns or plastic models can be used as expendable cores for precision casting molds.

This technique can also be used to directly make sand molds and cores. The original component CAD file is inverted to define a cavity rather than a solid shape and resin coated foundry sand is the dry powder feedstock. The laser scan causes polymerisation of the resin and the sand particles are selectively bound together to form a conventional shell mold. Very complex shapes can be achieved within an envelope of about 700x400x400mm (Figure 3).

Click Here to Close This Chapter

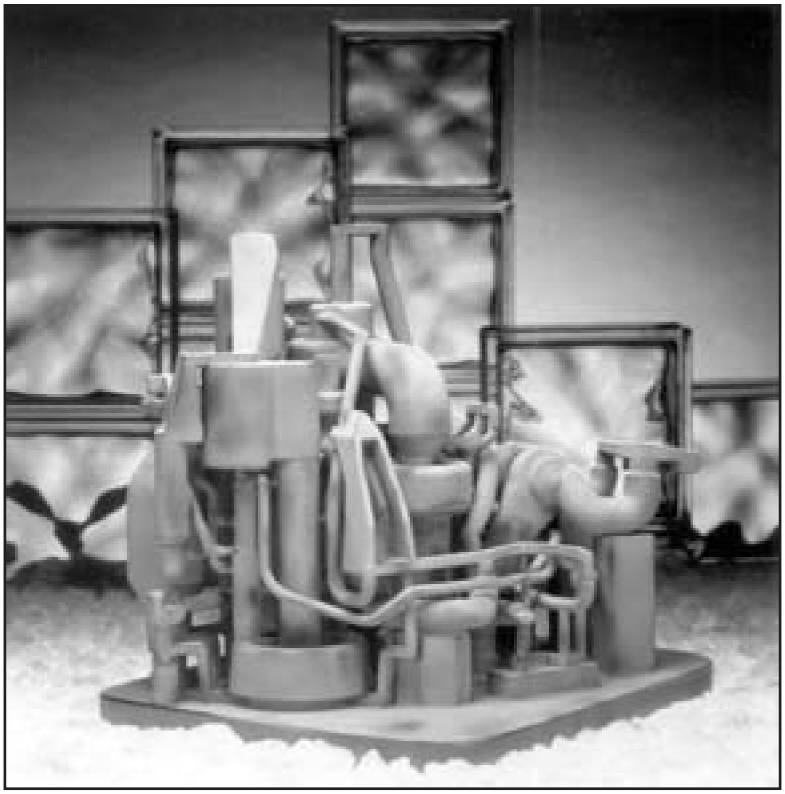

Figure 3. *Laser sintered sand mold (DTM Corporation).*

Laminated object modeling

With this technique, thin sheets of material (typically paper of 100-200 micron thickness) are built up layer-by-layer using a heat bonded dry adhesive. As each sheet is laid down a laser cuts the pattern of the part into the sheet. At the end of the process the cut out material is removed. The resulting model is similar in appearance and texture to machined wood patterns.

Fused deposition modeling

A CAD controlled extrusion head is used to deposit thermoplastic filaments in the desired pattern. As each pass hardens the next layer is deposited and a 3D shape is built up. Overhanging features can be built without supports.

Click Here to Close This Chapter

Ink jet technology

Droplets of thermoplastic are deposited by an “ink jet” mechanism and so build up the model.

Stereolithography SLA

Advantages

- Achieving best accuracies in the industry
- Market share and industry presence
- Capable of high detail and thin walls Good surface finish

Disadvantages

- Requires post-curing
- Some warpage, shrinkage and curl due to phase change. Greatly reduced with new epoxy resins
- Limited materials (Photopolymers)
- Support Structures always needed
- Removal of support structures can be difficult

Fused Deposition Modelling - FDM

Advantages

- No post curing
- Variety of materials
- Easy material changeover
- Office environment friendly
- Low end, economical machines
- Fast on small/hollow geometries

Disadvantages

- Not good for small features, details and thin walls
- Surface finish
- Supports required on some materials/geometries
- Support design/integration/removal is difficult
- Weak Z axis
- Slow on large/dense parts

Selective Laser Sintering - SLS

Advantages

- Variety of materials
- No post curing required
- Fast build times
- Limited use of support structures
- Mechanical properties of Nylon & Polycarbonate parts

Disadvantages

- Rough surface finish
- Mechanical properties below those achieved in injection molding process for same material
- Many build variables, complex operation
- Material changeover difficult compared to FDM & SLA
- Some post-processing/finishing required

Laminated Object Manufacturing - LOM

Advantages

- No post-curing
- No support structures needed

Diced scrap material provides this function

- Low maintenance costs
- No material phase change, no warpage
- No internal stresses
- Can fabricate large parts (550mm x 8OOmm x 5OOmm)

Disadvantages

- Surface finish/appearance
- Machinability of parts is geometry dependent
- Parts will not perform well in humid or wet environments
- Part strength varies according to orientation and geometry
- Excess material requires removal, internal cavities can be difficult
- Environmental concerns, outside venting required

Solid Ground Curing - SGC

Advantages

- High throughput, predictable build time
- Movable parts/assemblies
- Most economical for small parts
- No supports needed, No post-curing

Disadvantages

- Large, heavy machine, high maintenance
- Attended operation
- Material limitation
- Wax removal can be time consuming
- High waste and limited recyclability

Table 1. *Comparison or RP Methods*

Click Here to Close This Chapter

Casting methods

Sand casting

Using a pattern produced by one of the above methods, together with pieces to produce the running and feeding system, a sand mold is rammed around the pattern which is subsequently withdrawn. Alternatively the mold could be directly formed using the laser sintering method. Zinc alloy is then poured into the cavity. After solidification the sand is broken away and the casting extracted. The runner and feeders are then cut off.

Compared to a pressure diecasting, the surface of the casting is rough and the dimensional accuracy is much less. Machining to final size will be required to achieve close tolerances. The minimum wall thickness will be about 3mm.

Investment (precision) casting uses a disposable pattern on which to build the sand mold. Hence when several parts are required each will require a pattern. The dimensional accuracy of this method is better than that of conventional sand casting.

Plaster mold

Using the original pattern a model is created in a special rubber. This rubber model is then used to make permeable plaster molds. Pouring alloy into these plaster molds produces castings of very good surface appearance and of reasonable dimensional tolerance (0.15mm on 25mm). The low conductivity of the mold facilitates filling and thinner sections can be achieved than in sand casting (Figure 4).

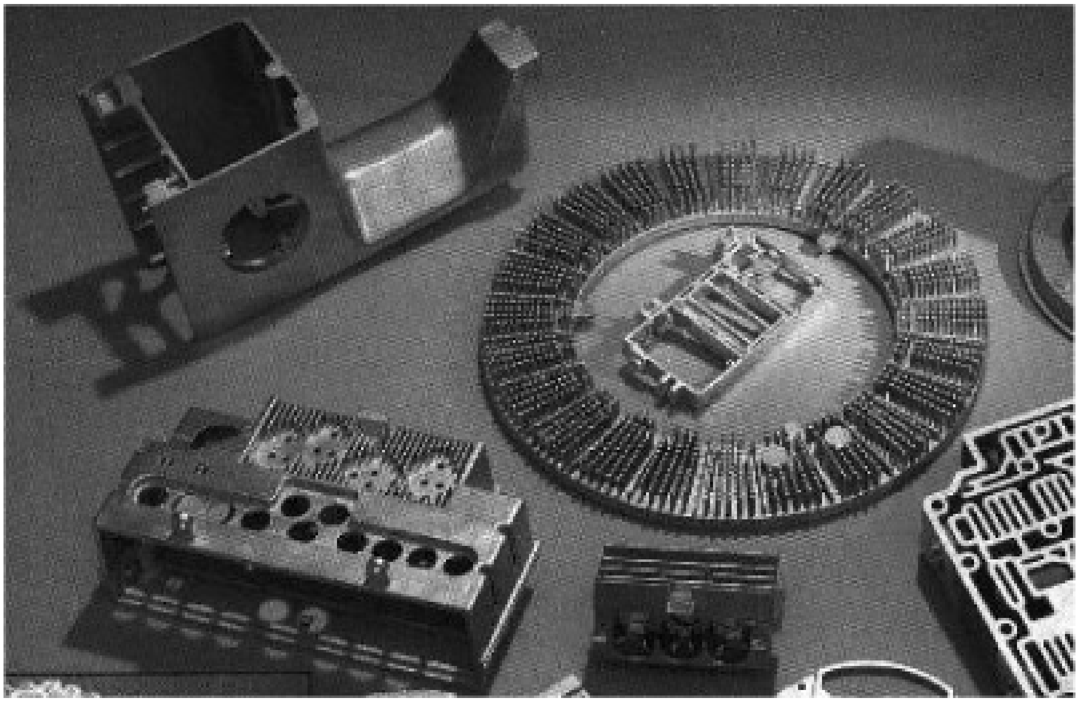

Figure 4. *Castings made in plaster molds.*

Rubber spin mold

In this process the pattern is pressed into uncured rubber which is then vulcanized and a runner system cut in with a knife. The rubber mold is mounted on a platen and spun at up to 5000rpm while the alloy

Click Here to Close This Chapter

is poured. The surface definition is comparable to a pressure die cast part and similar wall thickness can be achieved. Dimensional tolerance is not as good but is reasonable. Loose inserts of PTFE can be used to core bores.

The cost of the rubber mold is low and the molds can have a reasonable life. The mold surface deteriorates with use, the rate depending on the heat input. Zinc alloys with melting temperatures above those of ZA-8 will cause rapid failure. Provided the part is not too thick then, with care it can be possible to get a few hundred parts in ZA-8 or the 4% alloys. Doping the alloy, for example with cadmium, in order to lower the melting temperature is not recommended as such an alloy will be very susceptible to corrosion.

Graphite mold

The low melting temperature of zinc alloys allows graphite to be used as a die material. It is easily machined so production is fast and relatively low cost. The castings produced have good surface finish and tolerances are better than sand casting. The weakness of the graphite places restraints in the complexity of the parts which can be cast. Runs of several thousand are possible.

Process	Attributes	Tolerances
Pressure diecasting	Extremely smooth surface Excellent accuracy 0.8mm min wall (0.4 over small areas) size depends on machine	0.05mm/2.5mm
Graphite mold	Good surface and detail 2.5mm min wall max die block 400 x 400mm	0.3mm first 25mm +0.10mm/25mm
Sand mold	Rough surface 2mm min wall unlimited size	1mm first 150mm +0.15mm/25mm
Plaster mold	Smooth surface Good tolerance 1.5mm min wall up to 300mm cube	0.25 first 50mm +0.10mm/25mm
Spin rubber	Smooth surface 1mm min wall max 300 x 200 x 90mm	0.25mm/25mm

Table 2. *Comparative casting process information.*

Click Here to Close This Chapter

Prototyping Process Selection

The optimum prototyping process will produce the required properties at the least cost within the time constraints of the product development program. Process selection begins by comparing the critical properties of the end product made from the production alloy and process with the properties developed in the available prototyping process.

Strength, hardness, and resistance to wear vary with process, and sometimes vary significantly. However, some properties are essentially independent of process and alloy. Modulus of elasticity is nearly uniform for all zinc alloys whether pressure die cast, gravity cast or continuous cast and physical properties are similar. Specific gravity varies among alloys but is consistent for each alloy regardless of the casting process.

When the essential properties of the end product can be achieved by more than one prototyping process, other factors such as appearance, cost and delivery schedules can be factored into the process to determine the optimum process.

Table 3 checks the properties of zinc alloy pressure castings against the properties achieved in components made by the various prototyping methods. For a detailed comparison of alloy properties the ILZRO publication Engineering Properties of Zinc Alloys should be consulted.

Alloy	*UTS*	*Ductility*	*Min Wall*	*Chrome Plate*	*Wear*	*Creep*	*Fatigue*	*Impact*
3,5 or 7								
gravity cast in same alloy	lower	—	thicker	same	—	—	—	—
machined from concast bar of same alloy	same	lower	same	same	—	—	—	—
machined from existing pressure casting in same alloy *	same	same	same	same	—	same	same	same
gravity cast in ZA12	same	lower	thicker	worse	better	better	same	same
gravity cast in ZA27+HT	same	same	same	worse	better	better	—	lower
ZA 8								
Machined From concast bar of same alloy	same	lower	same	same	—	—	—	—
ZA 12								
Gravity cast In same alloy	same	lower	thicker	same	same	same	—	—
Machined From concast Bar of same alloy	same	same	same	same	—	—	—	—
ZA 27								
Gravity cast In same alloy	same	same	thicker	worse	same	—	—	—
Machined From concast Bar of same alloy	same	same	same	worse	same	—	—	—

* mechanical properties will be as stated provided excessive material has not been removed so that only porous centre is left.
Blank items mean that a direct comparison has not been made – consult an industry expert for advice.

Table 3. *Property compared with a pressure diecasting.*

Click Here to Close This Chapter

Rapid Tooling

Occasionally it is found that only a pressure die casting will be suitable for prototype testing or that there is a need for a pre-production batch of components that would be uneconomical to make by prototyping methods. In these cases a high pressure die will have to be made. This section outlines various methods which have been used, and are being developed, for the rapid and economic production of short/medium run tooling. This is an active research area where advances are quickly taking place.

Rapid machining

Originally defined as… machining applications where spindle speeds are above 12,000 rpm and feed rates are above 5m/min…rapid machining facilities now routinely cut aluminium at speeds of 30,000 rpm and rates of 15m/min. Somewhat lower speeds and rates are being achieved on harder materials such as die steels. The technique has the advantages of high metal removal rates, low cutting forces, minimal workpiece distortion and the potential for surface finishes of 0.1micron Ra.

The relevance to the production of pressure casting tools is that these advanced methods can reduce the time taken to produce conventional dies. This results in a decrease in cost and a significant reduction in lead-time. Figure 5 compares the times taken to make a small insert for a high pressure die.

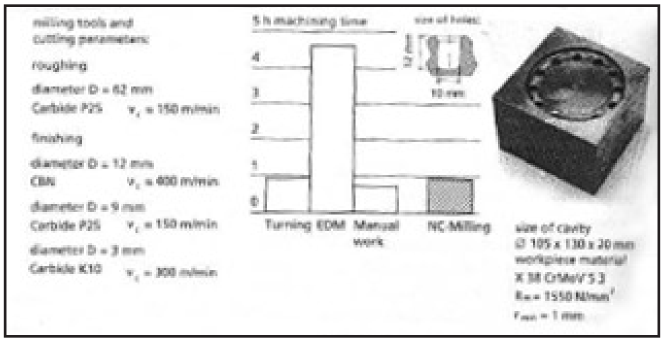

Figure 5. Comparison between the time taken to produce an insert using conventional or rapid milling techniques (Fraunhofer Institure).

Soft Dies

Fully hardened H13 inserts are time consuming to manufacture and alterations to the cavity shape are difficult to make. Time and cost can be saved by using a pre-hardened steel, such as P20. The lower hardness, 30Rc compared to the 45Rc typical of H13, leads to more rapid wear but does allow the cavity to be modified. Provided an excessive gate speed is not used, thousands of castings may be made and there have been many cases where commercial production volumes have been obtained using P20 dies. Care also has to be taken to keep die faces clean otherwise bruising and loss of sealing will occur.

Inserts may also be made from aluminium, although with much reduced life compared to P20 steel. Tests on anodized, machined aluminium dies have shown that several hundred castings can be produced. Gate speeds should be less than 30m/s and pressures should be as low as possible. Die temperature should be less than 200C and a die spray suitable for low temperature operation should be used.

A cost comparison indicated that the machined aluminium inserts were 20-30% cheaper than equivalent inserts in P20 steel. Cast-to-size aluminium inserts were around 50% cheaper than P20 inserts, but tests showed that they did not survive as long as the machined aluminium inserts.

Click Here to Close This Chapter

Cast Dies

Cast-to-size techniques may be used to produce steel toolsets. The starting point can be conventional patterns or the molds to make the steel parts can be directly generated using RP methods. Casting methods employed include Shaw, investment casting and Wheeldon Process. Allowances have to be made for the shrinkage which occurs during the manufacturing process, thus the dimensional accuracy of a cast cavity is unlikely to be as good as that of a machined one.

Sintered Dies

The laser sintering technique previously described can be used to bond metal powders. The powder is coated with a binder which is set by the heat of the laser. The part is then placed in a furnace, the binder removed and the steel infiltrated with bronze. A finishing operation is then needed to produce a smooth surface. Dimensional tolerance is typically 0.25mm. The mechanical properties are comparable to P20 steel.

A number of tests have shown that several hundred parts may be cast in aluminium alloy and that in excess of 10000 parts have been made in zinc alloy. In the case of the one of the aluminium parts (Figure.6) the cost to produce 300 components was 50% less than it would have been to machine them. It was also estimated that a time saving of 15% was achieved. Making zinc alloy lock actuators in a sintered die gave a cost saving of 50% compared with conventional soft tooling and reduced the tooling time from ten weeks to three weeks; 7000 castings were made before die wear was observed.

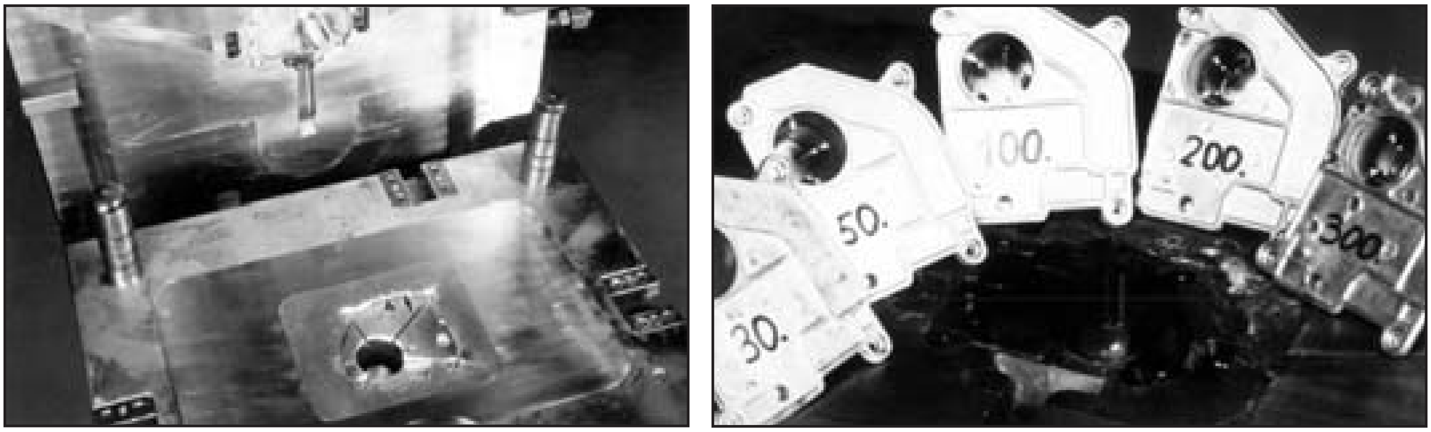

Figure 6. *Die made by laser sintering metal powder and the castings produced in it (DTM Corporation).*

Laminated dies

The laminated tooling concept uses the layered data from a 3D CAD model of a tool. Each slice is exported to a laser-profiling machine and defines one laminate of the tool. After cutting from steel sheet the laminates are de-burred, stacked and clamped together in a standard bolster. The accuracy will be high but, as the sheet currently used is 1mm thick, steps will appear on angled faces and will require dressing. The benefits of laminated tooling are claimed to be:

- The production of large-scale tooling, as the size of each laminate is only restricted by the size of the laser profiling bed.
- The inclusion of conformal cooling channels for decreased cycle times.
- The ability to replacement damaged or worn laminates.

Click Here to Close This Chapter

- The exchange of laminates for different profiles within a tool.
- Low cost and time of production.

The method is being developed not merely for the production of prototypes but for the medium run production of large castings where conventional tool costs are very high. An attraction of this method is that it is the only one which allows disassembly of the insert and hence the simple alteration of cavity shape.

Disassembly is possible because tests have shown that ingress of molten metal between the laminates is limited and that inter-laminate bonding will only be needed where a protruding sheet is unsupported. Elsewhere the laminates can be merely clamped.

Several hundred aluminium alloy castings have been made without die wear (Figure 7). This indicates that laminated dies have the potential to produce many zinc castings.

***Figure** 7. Laminated die made from steel sheets and the casting made in it (De Montfort University).*

Summary

Rapid machining will affect all aspects of die making and will reduce the time taken to make both conventional and RP dies.

Soft tooling is produced by machining and hence the accuracy and surface finish is identical to production tooling. Die life is sufficient to produce significant numbers of zinc alloy castings. The saving in time and cost over machining from tool steel may not be that great.

Cast-to-size tooling does not appear popular. The technique has been in existence for many years so its lack of popularity would indicate that there are drawbacks.

Laser sintered tools are being actively developed. Results to date indicate that die lives of over a ten thousand shots are attainable when casting zinc alloy. There are limits to the accuracy and finish that may make final sizing necessary.

Laminated tooling is also being rapidly developed. Die life appears adequate and accuracy should be good apart from stepping on angled surfaces. It is the only method which allows insert disassembly in order to modify the cavity shape.

Click Here to Close This Chapter