# Plastic Encapsulation for Semiconductors

The package has a number of functions:

- To protect the fragile die and wire bonds from damage.
- To protect the die from attack by chemicals and atmospheric water vapour, which could corrode its metallisation and cause device failure.
- To provide the main body structure of the component, for transport and handling.
- To carry component identification (coding).

The package is important in the overall appearance of the component, as well as determining its thermal and mechanical properties, and its material and construction must be able to withstand the full component operating temperature range without cracking, as this could break wire bonds or allow the ingress of chemicals.

At first sight, polymer encapsulation materials seem to compare badly with packaging techniques such as the hermetic metal cans used in the TO– series of transistors. Far from being an hermetic seal, polymers often actually *absorb* water!

However, the reason that polymer encapsulation has become a major packaging technology is that polymers provide sufficient performance for applications where the environment is less demanding, and give low cost and ease and speed of processing. This is especially the case for components used in surface mount technology, where cost and volume are important factors.

## Transfer moulding

In compression moulding, a thermoplastic or thermosetting resin is placed in a heated mould which is then closed, and heat and pressure are applied, causing the material to flow and fill the mould. If the material is a thermoplastic, the mould is cooled and the part removed. If the material is a thermoset or an elastomer, then it is left in the mould to cure and removed after the resin hardens (fully cured) and is cooled.

Transfer moulding is a variation of compression moulding applied to thermoset materials. The material to be moulded is placed in a heated cavity and forced into the mould proper once the desired viscosity is attained. Figure 1 shows the general arrangement of a transfer moulding press, and the process sequence is indicated in Figure 2.

Figure 1: Arrangement of a transfer moulding press

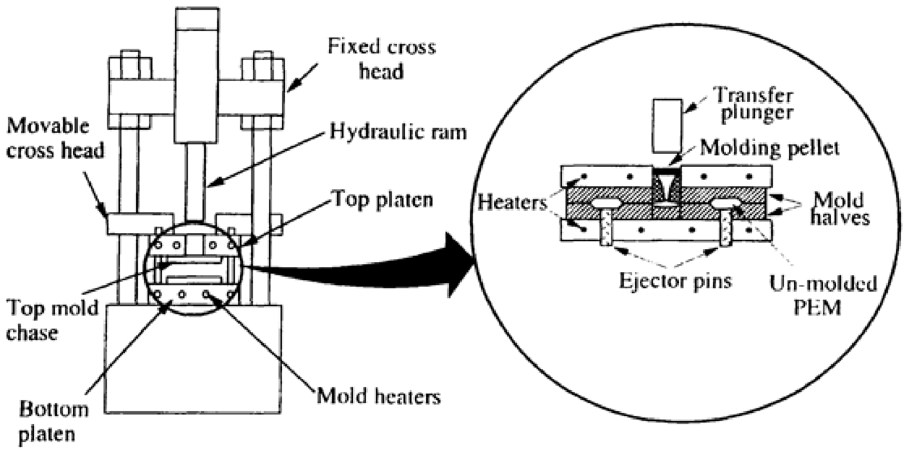
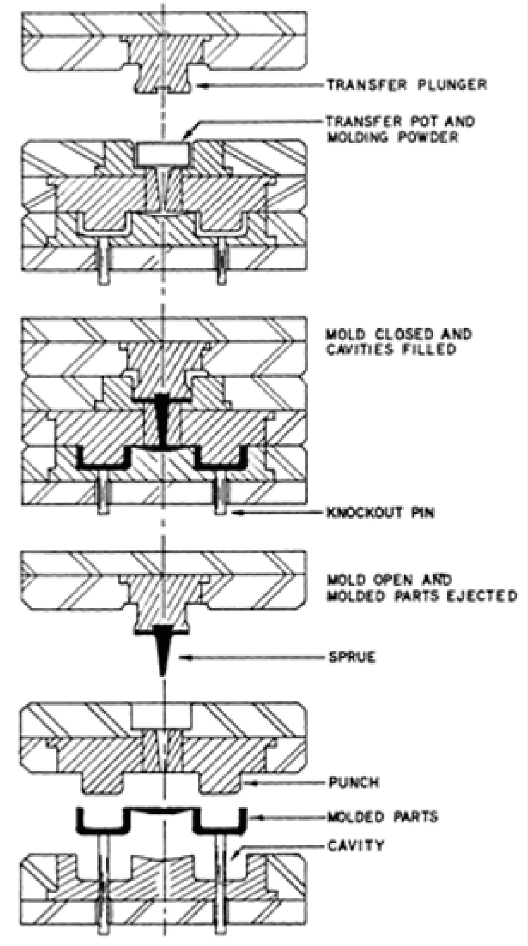


Figure 2: Pot or sprue type transfer moulding of thermosets



Advantages over compression moulding are that there is better control of material flow, parts have good dimensional accuracy, and thin sections and delicate inserts can be moulded easily. Control of the resin volume can be improved by specifying the moulding compound to be supplied in 'tablet shape', instead of using the more common granules.

Mould design and manufacture is an expensive undertaking:

- The mould must be capable of being split whilst hot to remove the mouldings, a process which is often helped by ejector pins.
- The mould is complex, with many pathways for the resin, whose design is critical to obtaining void-free mouldings.
- The mating surfaces must be flat, to provide a seal.

- The interior surfaces must be highly polished, to aid moulding release and may require to be textured to impart the desired finish to the mouldings.
- The mould must be capable of being heated to perhaps 200°C without distortion.

Moulds contains cavities for a number of packages: Figures 3 and 4 show how moulding compound is fed to each of these. A typical mould is built up of many components, and frequently individual cavities or groups of cavities are manufactured as inserts, so that some flexibility of product can be accommodated.

**Figure 3: Side and top cross-sectional views of the cavity and runner for a transfer mould**

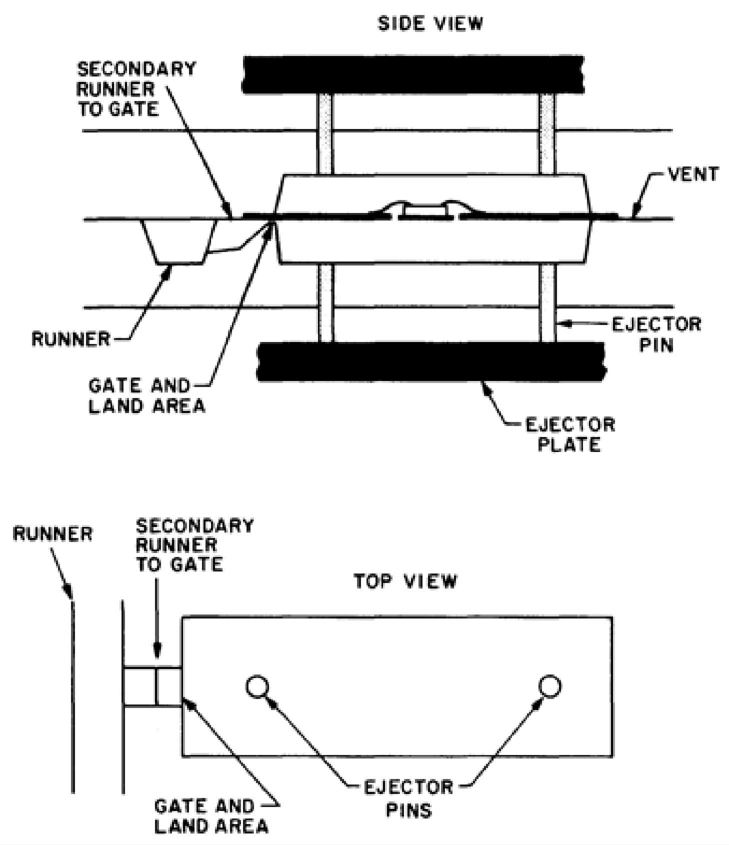
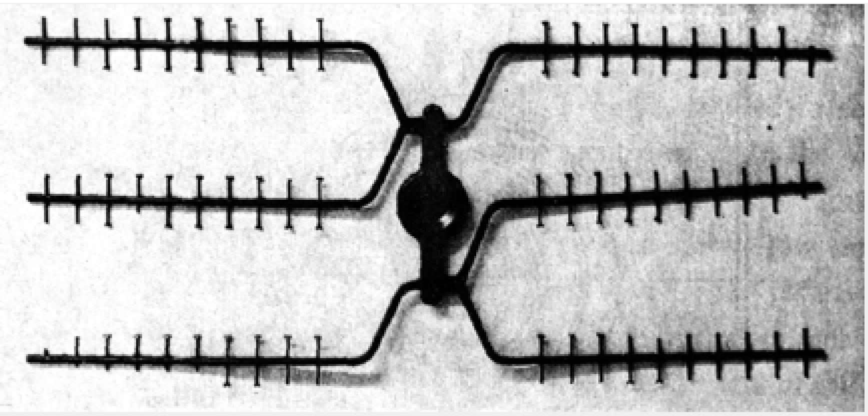


**Figure 1: Solidified moulding material showing the shape and complexity of the mould runners**



The moulding process takes place in a heated press, as considerable force is needed to hold together the halves of the split die against the insertion pressure acting on the surface area of the mouldings. The forces needed are substantial, depending on the part size, but moulding typically operates with presses rated from 20 to 200 tons. [Note that this figure represents the maximum closure force available, not the injection pressure!]

To ensure uniform expansion, lead-frames must be brought up to the moulding temperature (typically 175°C) before the halves of the mould are closed. In order to shorten the cycle time, the lead-frames are generally preheated to between 100–150°C before being loaded into the press.

Figure 5 lists the stages for the transfer moulding cycle. It must be pointed out however that the ‘transfer compound’ section of the cycle is actually quite complex, and the compound flows into an individual cavity during two periods of this phase. The first is the actual filling period; the second occurs after the last cavity has been filled and the full transfer pressure is applied to the compound, a process referred to as ‘packing’.

At this stage some further movement occurs, as compound is packed into any corners and entrained air or water vapour bubbles are compressed.

Figure 5: The transfer moulding cycle

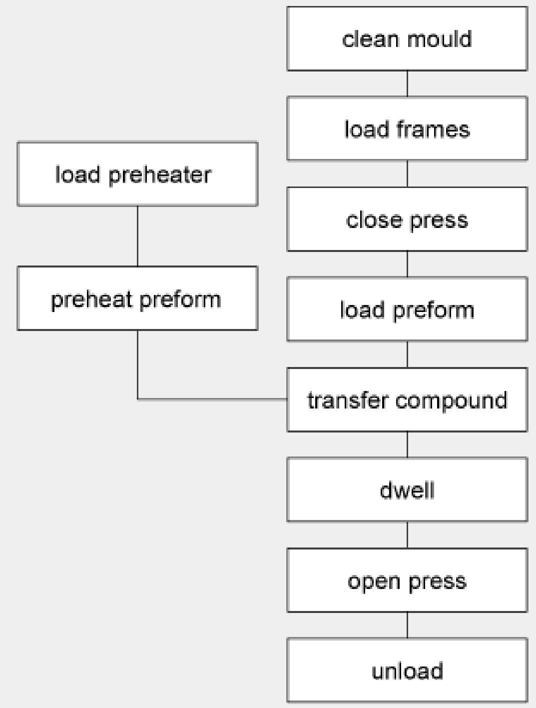
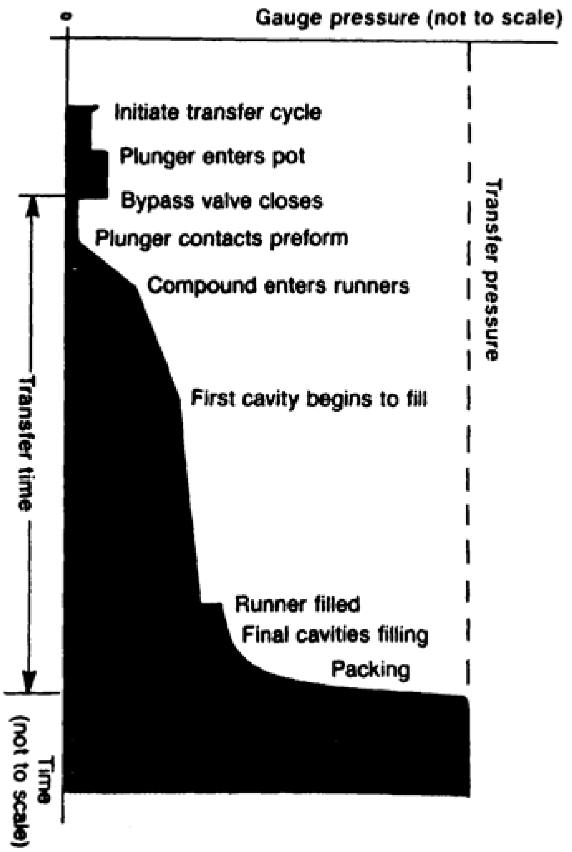


Figure 6 shows transfer cylinder pressure as a function of time. As the plunger comes into contact with the polymer and begins to compress it, the pressure begins to rise and continues to rise as the compound is forced out through the runners. As the compound travels down the runners past the gates, the flow resistance combines with the back pressure of the trapped air in the runners to cause the compound to flow through the gates into the mould cavities. This back pressure, which is substantially lower than the pressure applied to the transfer cylinder, is the only pressure which causes compounds into the cavities: whilst the cavities become full, they are not tightly packed.

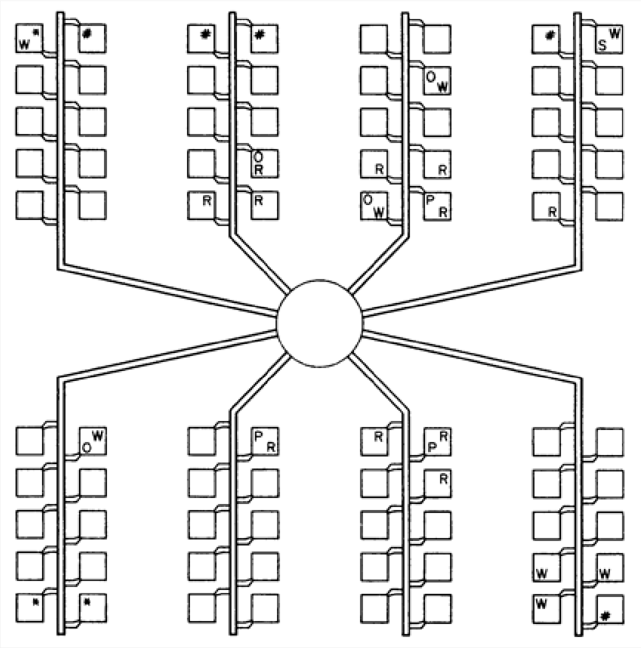
Figure 6: Transfer cylinder pressure as a function of time



Eventually the compound reaches the end of the runner and, with no exit, is forced more rapidly into the remaining cavities. These are filled at an ever increasing rate as fewer are left unfilled, the pressure to fill them coming directly from the hydraulic pump rather than the flow resistance. When the last cavity is filled, and flow approaches zero, pressure rises very rapidly towards the transfer pressure setting, and all the cavities are ‘packed’ simultaneously.

Transfer moulding is an operation where a number of different problems can arise, and much can be learnt from ‘mapping’ where the defects occur, as shown in Figure 7.

Figure 7: Mould mapping of typical moulding problems



The frequency of defects has been exaggerated for the purposes of illustration

The legend is: **O** = void; ***** = underfill; **#** = low density; **P** = overpacking;
**R** = resin bleed, **W** = wire sweep, **S** = die paddle shift

Transfer moulding is a comparatively lengthy batch process, fed from bonding machines which operate on strips of lead-frame which are completed comparatively quickly. There are two ways of organising the transfer-moulding operation:

- The ‘conventional’ process, where up to 10 or more lead frames are loaded into a mould which has one injection point for the resin (as in Figure 1). A slow cure resin is used in order to give the necessary control of viscosity, and the process includes an extended cure. A typical mould cycle time is 3–5 minutes, depending on the extent to which the parts are pre-heated before loading.

- The ‘automatic’ process, where fewer (typically 1–4) lead frames are loaded into each mould and multiple injection points used, with one injection point for every one/two cavities, and short (25mm) ‘runners’.

In the automatic process, the comparatively speedy filling cycle means that it is possible to use a quick cure resin and the 90–100 second cycle time includes 60 seconds of set/cure. However, a fast curing compound generally requires extra catalyst: as suitable materials often contain amines, there is some concerns as to whether long-term reliability might be affected.

With current materials, the press moulding operation is not the end of the encapsulation process. The final moulding cure usually takes place in batch oven and might be for as long as 5 hours.

## Materials

The following paragraphs describe the properties of moulding encapsulant polymers which are important in the component packaging process.

### Molten temperature

The polymers used in component packaging do not have a true single melting temperature, because of their composite nature and structure, with a large number of chemical bonds of differing strengths. The molten temperature is that at which the material shows liquid properties, although it will begin to soften well below this.

The molten temperature determines the requirements for transfer moulding, which indirectly impact on the yield and reliability of the components, as the populated lead frame has to withstand the moulding temperatures.

### Thermal coefficient of expansion (TCE)

Stress will occur in wire bonds, and in the adhesive joints to chip and lead-frame, because of differences between the TCE of the materials and that of the polymer body. This can result both in the formation of micro-cracks in the die joint which may ultimately accumulate in time to cause joint failure, and in the pulling off of wire bonds from the die pads.

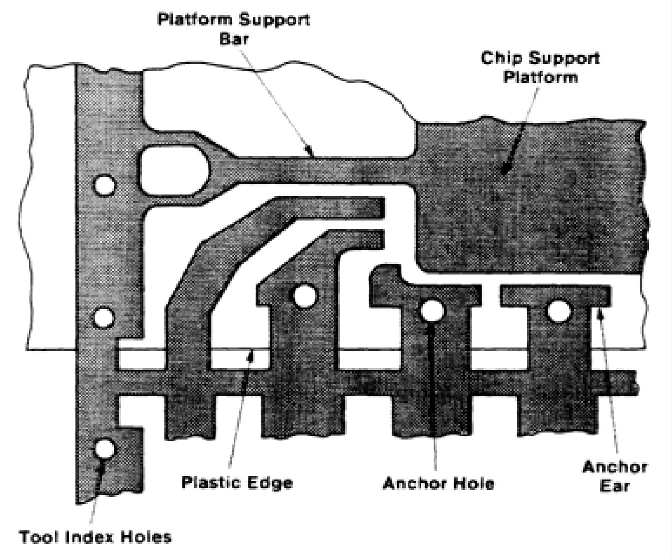
### Shrinkage

The moulding compound initially occupies the whole of the mould cavity, but many materials change dimensions and shape as they are cured, both in the mould and during post-mould cure. Whilst a degree of initial shrinkage is helpful in facilitating mould release, excessive shrinkage can put stress on the embedded components, leading to delamination or fracture. An important aspect is the mechanical balance of the moulding, so that stresses are even and do not lead to warping.

### Adhesion

Package cracking during reflow soldering can be a severe problem. This happens particularly with designs where the moulding is comparatively thin, and the die large. It is then difficult to provide a mechanical key between the lead-frame and the moulding compound in the way developed for earlier packages (Figure 8).

Figure 8: Typical lead-locking design for a dual-in-line package



Performance can be improved by enhancing the adhesion between mould compound and the lead-frame, die and die attach material. The main limitation has been found to be the polymer’s adhesion to the metal lead-frame, because the traditional 2–4µm thick silver plating is very difficult to adhere to. [Ganesan suggested a simple improvement, where the die pad has a central hole punched in it (the so called ‘window flag’) which maximises the interface between silicon and mould compound, which is intrinsically very strong]

## Dielectric constant

The dielectric constant is less important in component packaging than it is in substrate materials, but will influence the electromagnetic interference susceptibility of the component.

## Water absorption

The resin which forms the component package will absorb a small amount of water, the amount depending on the material used. The components may thus be susceptible to water absorption from the atmosphere, and some need to be packed and stored in vacuum bags and only removed just before assembly onto the board. For example, if water is absorbed by Ball Grid Arrays (BGAs), it can have important consequences for assembly process yield: sudden application of heat can cause the water to boil, expand and break the material apart, an effect known as ‘pop-corning’.

Because water is ionic, the water absorbed by the polymer can also affect its electrical properties, and can also assist electromigration on the die surface and corrosion of the chip metallisation and wire bonds. It may also be important for the reliability of the end product, depending on the conditions in which the part operates.

## Purity

As with die attach adhesives, moulding material need to be free of contaminants, in particular soluble ionisable halides, which currently have been restricted to a parts-per-billion level.

To prevent ‘soft errors’, the materials used for semiconductor products containing any memory elements need also to have a low alpha particle output.

Both these comments apply to all the materials which are brought together to form the moulding compound, to additives as well as to the polymer base.

### Thermal conductivity

The heat generated by the component has to be removed by conduction, either along the lead-frame or through the polymer. The thermal conductivity of the resin, which is a measure of how quickly heat will flow through the material, is therefore important to device reliability. If the thermal conductivity is insufficient to cope with the heat generated, the resultant thermal stresses may lead to component failure.

If the conductivity is sufficient for the heat to flow to the package surface, but it cannot then escape quickly enough by passive convection, heat sinks are used to increase the surface area and aid heat dissipation. These may be fan assisted to move hot air away from the component to optimise the cooling process.

### Flexibility

The material must be able to withstand all the different CTEs of the other materials in the package. Combined with the requirement to withstand vibration and yet be rigid enough to hold the whole component together, this greatly restricts the number of suitable materials.

## Practical materials

Given the stringent requirements, it is not surprising that the industry has gravitated towards a relatively few materials. It has been commented that all material suppliers use one base resin which originates from a single source, so there is an obvious threat to supply! The main material used is an orthocresol-novolac epoxy such as Sumitomo 6300.

A different material, with a base of bisphenyl-epichlorohydrin epoxy, has been making an entry since 1994. This is more expensive, but makes possible a reliable thinner package. There is however a processing hazard, in that the material sticks well to the mould!

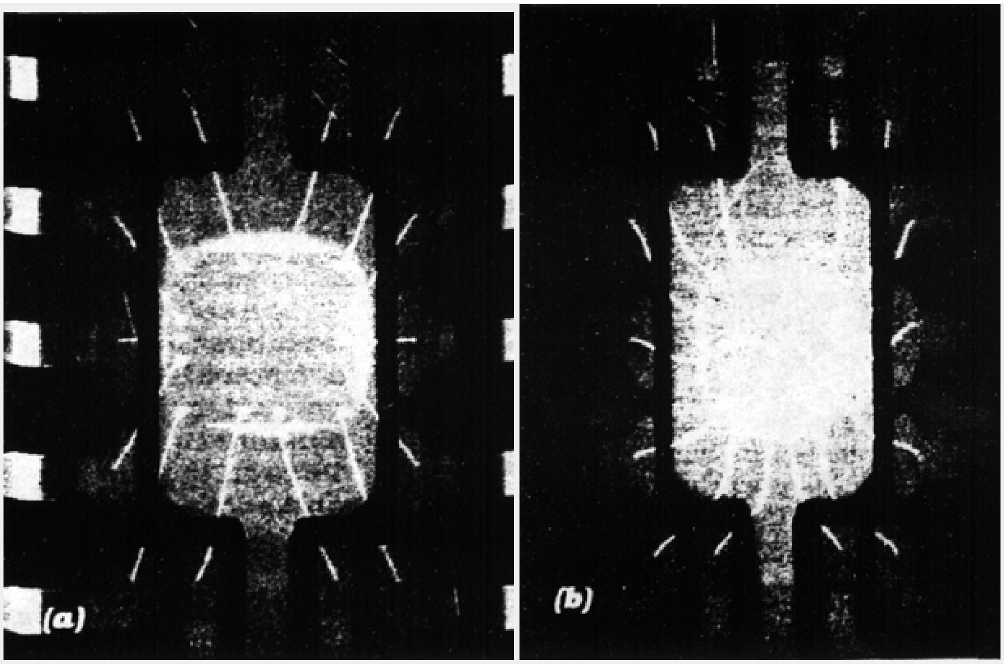
Moulding compounds contain a range of different additives:

- Silica is provided to add bulk and modify the flow and thermal properties of the compound. The shape of the particles is important, and a mix of spherical and crushed silica is common.
- Antimony and bromine compounds are added to give flame retardence.
- Globules of silicones may be added to give stress relief.
- Alumina and aluminium nitride particles are added to enhance thermal conductivity. Unfortunately aluminium nitride in particular has angular particles which are abrasive, leading to excessive mould wear. A recent innovation has been to to coat the material with silica (‘Silica Coated Aluminium Nitride’), which protects the mould, and does not unduly reduce thermal performance.

### Wire sweep

Mould wire sweep or ‘bond scouring’ (Figure 9) is non-elastic deformation of the bond wires caused by the force exerted by the viscous polymer as it flows into the cavity. Because of the nature of the bond wires, differences in design, and factors affecting the polymer flow, apparently similar packages may suffer substantially different degrees of mould sweep.

**Figure 9: Wire sweep in a 14-lead SO- package (a) negligible sweep; (b) excessive sweep**



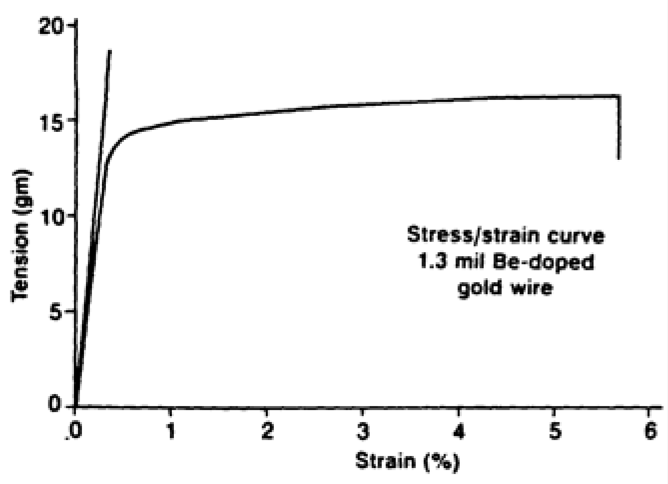
A typical criterion for mould wire sweep is that, when examined using X-ray techniques, any bond wire should not be closer than 250µm to its adjacent lead finger. As the measurement of every wire becomes very tedious, the sampling plan should take into account that the four corner wires are generally most susceptible to sweep, the first unit to fill may have swept wires.and the last unit to fill generally has the most severe sweep.

Controlling sweep is a complex function of the bond material, the device design, the melt properties of the polymer, the mould design and the moulding parameters, as is shown in the paragraphs below. It must be remembered however that the choice of moulding process involves issues other than wire sweep, and the results must be balanced against other constraints, such as moisture resistance and surface finish.

### The wire bond

The stress-strain curve for annealed pure gold is unusual: even very low strains result in plastic deformation, which is retained as permanent ‘set’. Adding trace amounts of beryllium extends the elastic region to around 80% of ultimate strength (Figure 10) and wire of this type is resistant to mould sweep until its yield strength is exceeded.

**Figure 10: Stress/strain curve for 33µm diameter Be-doped gold wire**



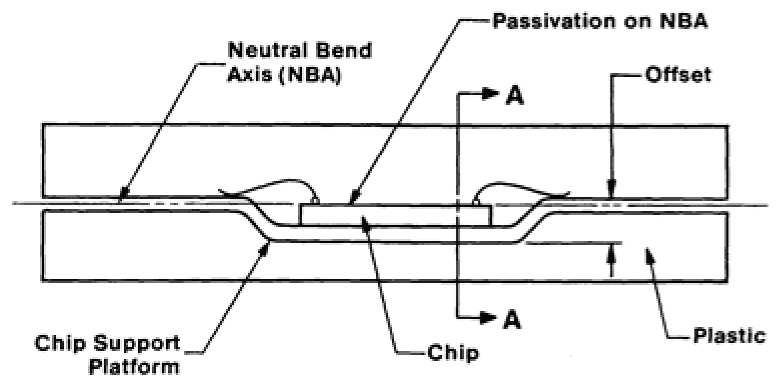
The addition of trace amounts of beryllium gives the gold a more extensive elastic region before the curve departs from Hooke’s Law

Such wires will tend to pull back to their pre-mould positions before the compound cures, although the extent to which they can actually move will depend on the viscosity of the gelling resin.

Arguably the most significant factor affecting the ability of the wire to resist sweep is its diameter, but bond design is also important as long wires distort more, so both lead-frames and die bond pads should be designed to control bond length.

Tay showed that better results are obtained with the die surface at or below the level of the tail bond (Figure 11), and with a reversed or standard loop rather than a parabolic loop. Appropriate shaping of the wire bond produces different flow distributions and alters the incidence of wire sweep and lift off problems during moulding.

**Figure 11: Reducing cracks and mould sweep using a lead-frame offset**



### Moulding compound

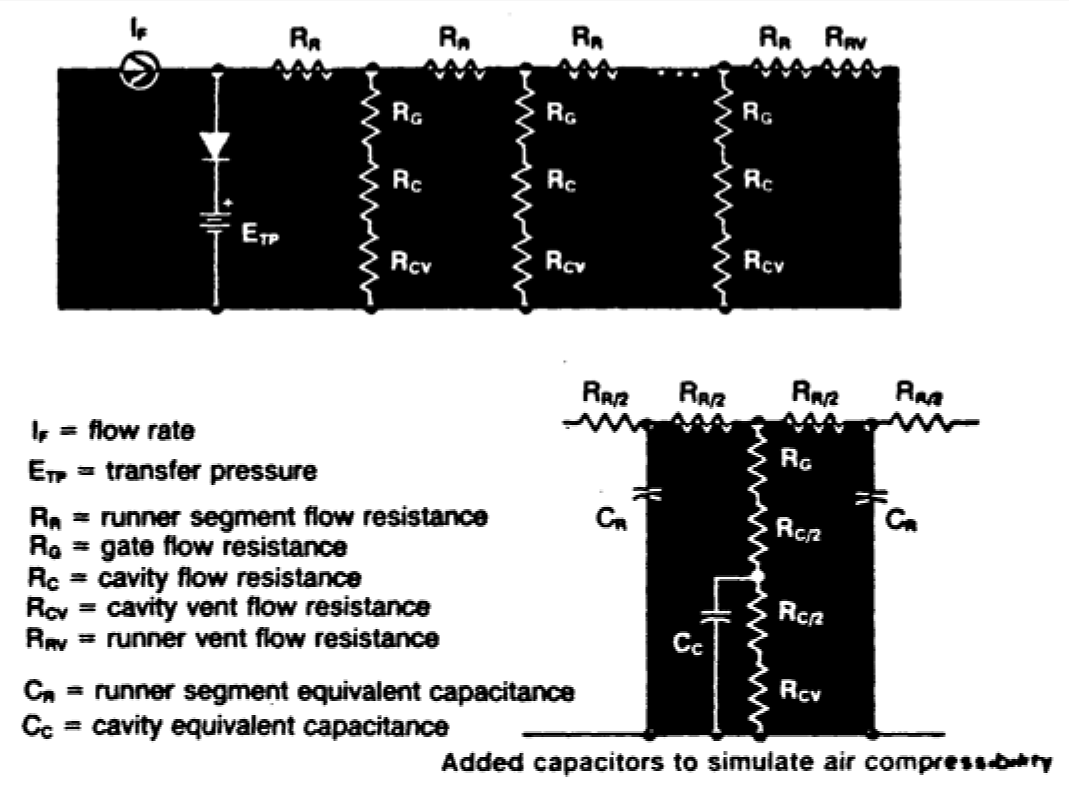
Wire sweep is affected by entrained air, by the characteristics of the filler, by the changes in viscosity with time, and by the compound's response to preheat. Under-heated preforms will be too viscous initially, affecting the sweep of initial units, whereas overheated preforms will set too quickly, affecting the sweep of the final units and interfering with mould packing.

### Mould design

Reducing the **gate area** forces the compound to move further down the runner to develop sufficient back pressure to fill the cavity. This longer runner 'tongue' means that more cavities fill simultaneously so that individual fill rate is reduced, and the final cavity filling rush is controlled by the increased gate resistance. However, gates which are too small may become blocked by large particles of filler in the compound.

Examination of an electrical analogue (Figure 12) for the mould also suggests that reducing the **runner resistance** will result in lower back resistance, allowing more cavities to fill at the same time.

**Figure 12: An electrical analogue of the press/mould transfer system**



The change in flow resistance as the compound front pass through the mould can be accommodated by a scale change in the resistors.

Reducing the **vent size** will provide some compressed air resistance in series with the gate, reducing the fill rate. Also, by reducing the resistance of the gates towards the end of the runner, the last few cavities can be made to fill together, thus absorbing the total flow. It must be remembered that the total flow rate into the mould is kept constant because compound is forced out of the pot at a rate determined by the flow control valve.

In designs with off-centre gates, there may be variations in degree of sweep from strip to strip because of differences in the **angle of entry** of the compound, with runners on different branches filling at different rates.

### Mould process parameters

Mould **temperature** is a compromise: if too cold, the compound will have a high viscosity, affecting the sweep of initial units; if too hot, the compound will cure too rapidly.

**Transfer rate** also has a direct affect on wire sweep and lift-off problems:

- A high rate is desirable to reduce cycle time, but will place a high load on the wire bonds.
- A low rate will allow the moulding compound to cure partially and become very viscous before the end of the cycle.

The free plunger travel before the plunger contacts the preform (the ‘transfer plunger height setting’) also has a strong effect on sweep.

**Transfer pressure** tends to affect only the final stages of filling and mould packing, but has a direct affect on sweep: the higher the pressure, the greater the sweep.

### Package warping

Warpage is a highly non-linear phenomenon which is difficult to analyse, particularly when the glass transition of the moulding compound is considered. It also has to be remembered that each package is only part of a larger unit, and the behaviour of a lead frame with multiple units, or even multiple rows of units, will be substantially different from a single package.

In practice, the entire lead-frame tends to curl up and assume a concave shape as seen from the top. This raises manufacturing problems, especially because affected strips are difficult to load into carriers or guide by feeders/conveyors to the next work-station.

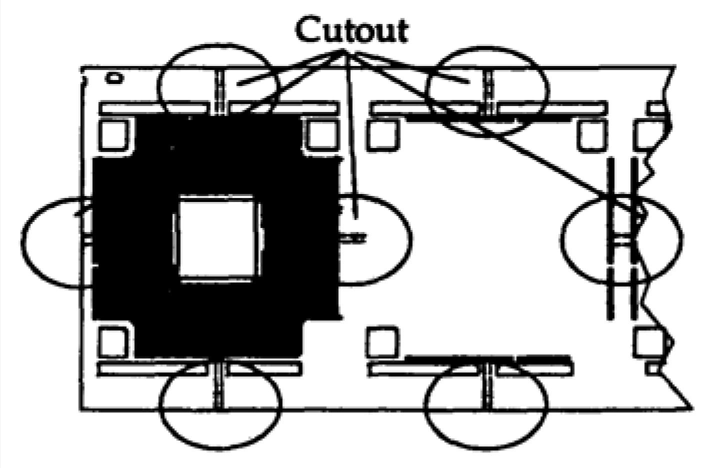
There are a number of potential causes of warping:

- At lead-frame **pre-heating**, due to improper heating, premature clamping of the mould and uneven expansion of the copper lead-frames against the hot steel mould.
- After moulding because of the **thermal mismatch** between the mould compound and lead-frame.
- Examination of PQFP processing showed that the temperature gradient within the package during **cooling** contributed significantly to the final bow, which was proportional to the square of the package length.

Analysis suggests that the temperature at which buckling starts depends on the **lead-frame thickness**, with a 0.1mm thick lead-frame buckling at 75°C , compared with 150°C for 0.3mm stock of the same design.

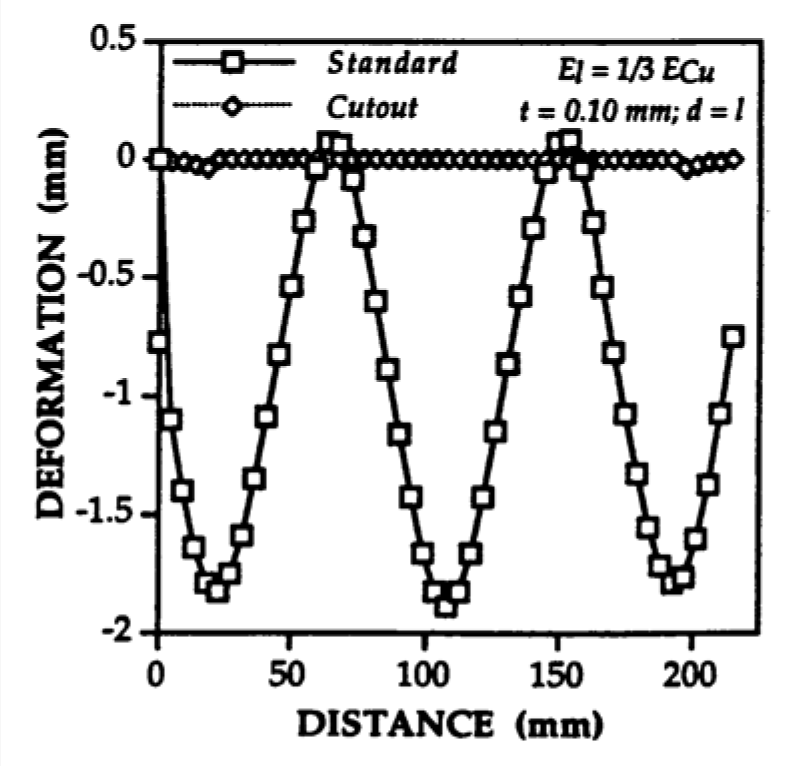
To minimise the warpage influence, it was found that cut-outs should be inserted into the **lead-frame design** wherever possible as shown in Figure 13. Naturally, the cut-outs have to be incorporated in such a way as to prevent the lead-frame ‘falling apart’, and sufficient rigidity is needed for the frame to be handled. However, continuous lengths of metal can be reduced to a half or a third, as a result of which the critical temperature decreases and the strip becomes structurally stiffer. Slightly local deformation occurs, but the previous curvature disappears (Figure 14).

Figure 13: Suggested lead-frame design with special cutouts for stress relief



Nguyen, Chen and Lee 1994

Figure 14: Strip deformation with standard lead-frame and lead-frame with cutout



## Reliability issues

Typical causes of unreliability encountered in plastic packaged devices which are the result of poor **process control** are:

- Voiding in the die attach adhesive
- Non-sticking bonds due to pad contamination or poor bonding conditions
- Incomplete cavity fill
- Wire sweep from excessive polymer transfer rate
- Wire breakage due to sweep or handling
- Voids in the moulding compound

Defects arising from **improper material selection** can range from passivation cracks, metal line shifts, delamination of the epoxy/die interface, and corrosion.

**Temperature and humidity** combine together to cause various moisture-induced failures such as device parametric shifts from increased leakage current, increased line resistance from aluminium corrosion, and poor contact from gold-aluminium bond corrosion.

For such failures to occur, a moisture film is needed at the die interface and this moisture can only come from two routes:

- Along the interface between lead-frame and encapsulant, starting at micro-cracks or delamination at the periphery of the package. These may occur during cooling after post cure, trim and form, or packaging and sorting operations.

- Through the bulk of the encapsulant. The moisture absorption of a material is related both to the base resin and to the shape and surface treatment of the filler. Diffusion characteristics also depend on the curing profile and the temperature and humidity history of the compound - once water has permeated an epoxy, some permanent structural damage will occur even after baking.

**Stresses** in the package result from differences in TCE between the materials used. Finite element analysis gives a useful insight into the interaction between the package elements, but the models used have to be validated by experimental measurement. This can be carried out using interferometry, X-ray diffraction, or piezo-resistive devices built on silicon. The last of these is the most suitable for in situ measurements, and can simulate even large die, using multiplexing techniques to make contact with strain gauges over the whole die surface. By selecting the proper crystal orientation and monitoring the doping level, designs can also be tailored to provide a picture of the stresses within the die in three dimensions.

Although the die attach material imparts stresses to the silicon, their magnitude is small compared to the stresses produced by the moulding compound. Ways of reducing these stresses can be grouped into two broad categories:

**Material-related**. Developments in resin technology have reduced TCEs to around 15ppm/°C. However, further improvements will require radical changes in resin chemistry and there is a limit (≈80% by weight) to the amount of filler that can be added without affecting the resins ability to be moulded. There is also a conflict in that low flexural modulus, which helps thermal shock resistance and soldering performance, is linked with high TCE, which gives higher moulding stresses and greater potential for wire bond fatigue failures during cycling.

**Process-related** solutions involve decoupling the die interface from the shrinking epoxy using polyimide or silicone based coatings which can be applied by spinning or screen printing at wafer level and by dispensing at die level.

Where the die coating thickness is not critical, ‘glob’ dispensing of silicone can reduce moulding stresses at a fraction of the cost. However, since the material is dispensed after wire bonding, there are relatively high temperature cycling failures due to thermal mismatch between silicone and epoxy. A coating of at least 10 times the ball bond thickness is needed to avoid metal fatigue, with the wire yielding at the ball neck.

The best current approach to reducing stress, which is a critical issue with linear devices, seems to be a combination of common sense device layout (for example placing stress sensitive features away from the die corners), silicone gel coatings or polyimide films, and low stress moulding compounds with low TCE and high flexural strength.

Source : http://www.ami.ac.uk/courses/topics/0269_pem/index.html