Design guidelines

for product engineers

on the thermoforming process

U aangeboden door:

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SIXTH FRAMEWORK PROGRAMME

ProducentenVereniging Thermoplasten

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1. Executive Summary

This report reviews the choices that may be considered for thermoforming processing. Thermoforming is a broad technology genre so the report gives some background information to the various thermoforming process sub groups and links the tooling considerations to these technologies. The tooling options for high pressure plug assisted, moulding which is a significant subgroup, is also discussed in some detail.

This report considers the factors deemed to be important when selecting materials for the construction of moulds for the thermoforming process. It does not consider design issues such as draft angles, corner radii and draw ratios because these should have been addressed during product design.

The selection of mould materials is dependent on several factors including cost, quantity and quality of parts required the capability and lead time of the toolmaker and the thermal characteristics of the material.

Additionally to comply with the dimensional and thermal requirements of the thermoforming process other tooling material requirements need careful consideration. The material must be capable of thermal cycling, be able to transmit vacuum from all areas of its surface, be robust but easily modifiable and be dimensionally accurate with known shrinkage characteristics.

The literature confirms that aluminium is the mould material of choice for high volume production work, meeting all of the characteristics outlined above. The material is readily available, easily worked integrating into CAD/CAM systems and is relatively cheap. Importantly it also offers excellent thermal conductivity: moulds are a fundamental part of the heat transfer process in thermoforming and determine the consistency of the mouldings from both a dimensional and quality perspective. Heat transfer characteristics maximises the efficiency of the production cycle and once the economics of scale become favourable it this characteristic that confirms on aluminium its dominant status.

For prototype or low volume application other materials become worthy of consideration. In addition to the ubiquitous aluminium these can include resin (including metal filled systems) syntactic foam, composite board, plaster, and wood. Prototype moulds and moulds for low volume applications are usually fabricated from more easily worked materials where the heat transfer benefits of aluminium associated can become secondary considerations. Data sheets for aluminium suitable for thermoforming tooling have been identified but none of the major suppliers make a point of supplying grades specifically for thermoforming.

Two non-aluminium materials were investigated; filled epoxy resin systems and machinable polyurethane board. These materials are indicated for several applications of which thermoforming tooling is only one. Specific information linking the material to thermoforming is therefore limited, but data sheets for these types of materials used by the consortium partners have been reviewed

Finally in the course of the study the literature unearthed a series of articles that linked thermoforming and tooling materials to process simulation. A brief synopsis of this area is included for completion.

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2. Introduction

Thermoforming usually describes a process whereby a thermoplastic sheet is heated sufficiently to soften it and then cooled to become solid again after forming to the required shape. Wagenknecht[1] stated that technical terminology has not been standardised, and different terms are used for the same thing, e.g. thermoforming, vacuum forming, heat forming and deep drawing can often be interchanged. The VDI recommended description was “shaping of sheets of thermoplastics materials”, and the process was defined as “stretch forming in which the heated firmly clamped blank is stretched. During stretching the wall thickness of the blank is reduced”.

However, the process is not restricted to sheet but can for example, be used for joining pipes by forming sockets and for making power cable spacers by winding preheated plastic rods around formers. Thermoforming can involve bending and folding sheet following localised heating, free forming by inflation without moulds and draping heated sheets over jigs. However, most thermoforming involves shaping extruded sheet with moulds using vacuum or compressed air or a combination of the two and this review is concerned with the tooling used for this process.

Thermoforming with moulds can be divided into two quite distinct processes, which are also defined mainly by two product areas:

1. Single-trip packaging using thin gauge sheet of 1.5 mm or less which can be used off rolls, heated, formed and cooled very quickly.

2. Durable products such as door panels, caravan roofs etc. using 3 mm or thicker precut extruded sheet which can take relatively long times to heat up and cool down in the thermoforming process.

2.1 Thin Sheet Thermoforming

Thin sheet thermoforming can produce very high output rates of thin wall containers, due to high area utilisation and in some cases involve forming with the extrusion. Economies result from immediate recycling of skeletal waste and trimmings with the extrusion edge trim. Coextrusion of barrier sheet and form-fill seal processes within a multistation machine are possible[2]. Unlike injection moulding, wall thicknesses will be variable but providing these are kept within reasonable limits, particularly with barrier sheet, then this is adequate for most single trip short life applications.

With thin sheet, heating and cooling can be rapid, area to thickness ratio can be much higher than with injection moulding, and trimming can be in-situ. A single machine with roll feed and comparatively low cost tooling can easily outperform injection moulding, but very importantly the trend towards multilayer barrier packaging for long shelf life normally eliminates injection moulding.

2.2 Thick Sheet Thermoforming

In comparison to injection moulding, manufacturing costs for thick sheet forming are high due to extruded sheet being the starting material and long cycle times resulting from long heating and cooling times. Furthermore, there is the trimming of thick sheet after forming. However, thermoforming can compete with injection moulding for products where low tooling costs make low production volumes economic, short tooling lead times are important and very large areas are needed. In principle, size is limited only by the width of available extruded sheet. The process is ideal for products such as caravan roofs, bathtubs etc., but may sometimes be used for short run prototypes and pilot production prior to injection moulding higher volumes.

A particular advantage of thermoforming is the economic manufacture of large parts such as 3 m x 2.4 m x 13 mm camper tops and boat hulls with reduced costs and relatively low tooling costs. Thickness can be increased to improve performance and coextruded sheet will provide specific surface properties [3] and bury regrind.

Disadvantages described include cost of using extruded sheet, dimensional accuracy is confined to one side, and trim material can represent from 10 to 50% of the sheet that must be re-used.

2.3 Tooling

With such a range of sheet thicknesses, shapes and sizes, and runs varying from a few prototypes to thousands per hour, tooling materials and manufacturing is very diverse ranging from precision CNC machined aluminium to craftsman shaped hardwood. There is very little published technical data on tooling and performance details and technical comparisons are at best sketchy. It is evident that tooling selection and performance will be much more influenced by lead times, surface friction, and sheet contact/cooling efficiencies than for injection moulding.

A fundamental difference between thermoformed sheet and injection moulding is that in thermoforming, wall thickness cannot be accurately controlled nor selectively made thick or thin, or provided with solid ribs and bosses for inserts, whilst shrinkage during cooling makes tight tolerances difficult to achieve. Surface finish may also be a problem e.g. through changes in gloss during heating, variable contact with the mould, marks caused by plug assist, or lack of surface detail[(3)].

The thermoforming process has attracted significant attention from computer aided design and processing researchers for predicting influence of variables on final wall thicknesses but published papers on properties such as friction and biaxial stretching are relatively few.

The wide range of tooling materials and manufacturing techniques is covered mainly by papers over 10 or more years ago whilst in more recent articles describing vacuum forming investigations, other than the dimensions of the mould shape, details of the tool material, overall design etc. are usually sketchy or omitted altogether.

In order to give an overall picture of the tooling requirements and due to the large diversity of thermoforming operations, most of the articles covered are not directly concerned with tooling but many have a bearing on tooling materials and design. Although not made to directly match the shape of the mould, the plug assist tool has a considerable influence on the wall thickness distribution and this has been included as part of the tooling.

2.4 Literature

The literature search did not find any good technical articles on tool design or tool materials. Information is scattered throughout books, editorial reviews on tool and tool material suppliers and commercially biased information in journals, trade literature and (surprisingly) conference proceedings. Data also exists in papers covering plastics tooling generally and in a book on alternatives to injection moulding[(3)]. There is however a short section on “design of tools forming thermoplastic sheets and foils with vacuum or compressed air in the book “Plastics molds and dies” by Sors, Bardòez and Radnote (1981)[(4)] and Gruenwald in “Thermoforming, a plastics processing guide”[(5)] has recommendations concerning such factors as control of wall thickness, prevention of webbing and mould materials. There are useful practical details in a book by Illig/Schwarzmann[(6)] and one by Throne[(7)].

As so many variables exist which influence the way the sheet forms in or around the tool and hence the final moulding dimensions, as well as cycle times, a brief review of the different systems and some of the variables have been included as well as measurements of friction between sheet and tool material. Finite element analysis for predicting final wall thickness is also briefly reviewed as such factors as hot sheet to plug friction is included and the plug (in plug assisted forming) is part of the tooling.

As literature searches for tooling information needed to be comparatively broad, they uncovered a surprising number of technical articles on computer simulation and related topics. Rather than discarding them it was decided to briefly summarise the abstracts as they could well be of relevance to the programme as a whole. This was in addition to computer simulation articles selected for relevance to tooling.

Many of the articles of US origin used Imperial units. These have been converted to metric ones in most instances.

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3. Thermoforming process

These are described in books by Throne[7], Illig[6], Gruenwald[5] Sors, Bardòez and Radnoti[4], Avery[3] and the British Polymer Training Association[8]. There are three basic procedures and numerous variations; many of these giving improved degree of draw and/or more uniformity of wall thickness. The basis of these processes is that a sheet of plastic is heated until it softens, clamped to form an air seal and then sucked and/or blown to the required shape, cooled and removed.

The three processes as described by Gruenwald[5] are:

1. Billow, bubble or free forming
2. Cavity forming
3. Drape forming.

The remainder are mainly variations of these three processes.

3.1 Bubble Forming

(figure 1)

The heated sheet is clamped and shaped by air pressure or vacuum such that pressure difference causes the sheet to bulge forming dish or dome shapes. This is a useful system for forming transparent materials such as PMMA, cellulosics and polycarbonate where good optical properties can be achieved best with no mould contact. As the sheet becomes progressively thinner towards the apex, a height to diameter ratio of 75% is a practical limit.

3.2 Cavity Forming

(figure 2)

This is also called “straight” or “simple” vacuum forming, and uses a mould which is termed female, negative, concave or cavity.

Figure 1. Bubble Forming

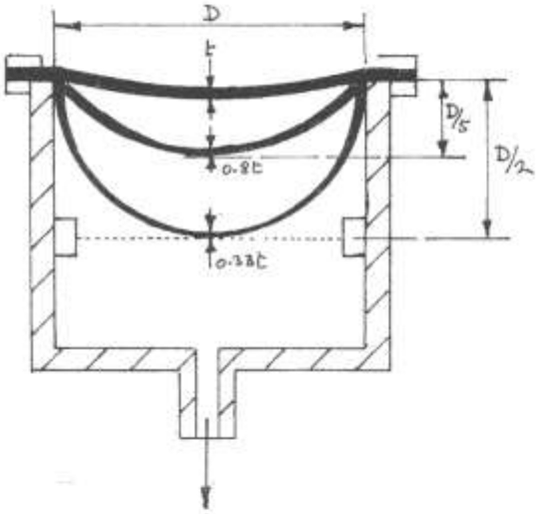
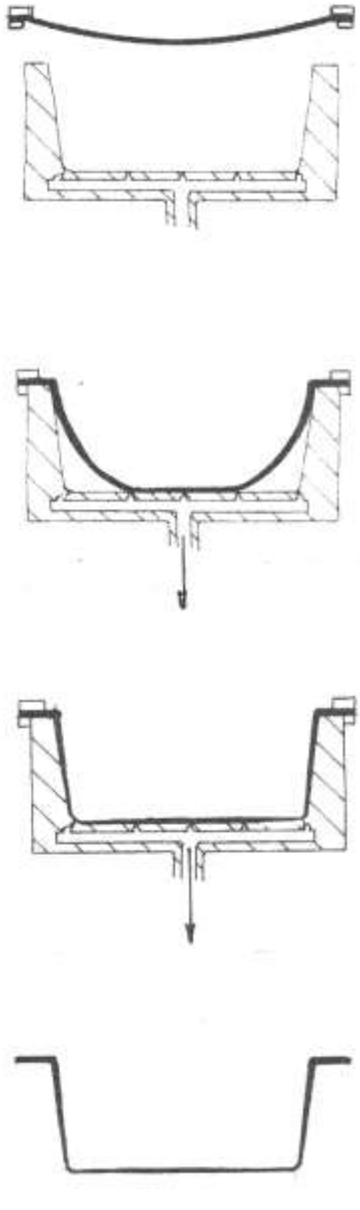


Figure 2. Cavity Forming



After heating to soften, the sheet is clamped over the mould opening, and sucked by vacuum into the mould, where it is cooled to the shape of the mould. The resulting moulding will usually be thinner at the bottom, particularly at the corners; (figure 3) the deeper the draw, the thinner it will be. Shrinkage during cooling aids moulding removal.

3.3 Drape Forming

(figure 4)

This uses a male, positive, convex, or drape mould. In this case, the heat-softened sheet is lowered in its frame, over the male tool to form a seal at the base, vacuum then being applied to suck the sheet on to the mould. During the frame downward movement, the sheet will contact the flat raised area of the mould and start to solidify at about its original thickness, whereas the remainder will be stretched during the remaining movement and the vacuum's pull.

Figure 3. Wall Thickness Distribution in Cavity (negative) and Drape (positive) Forming.

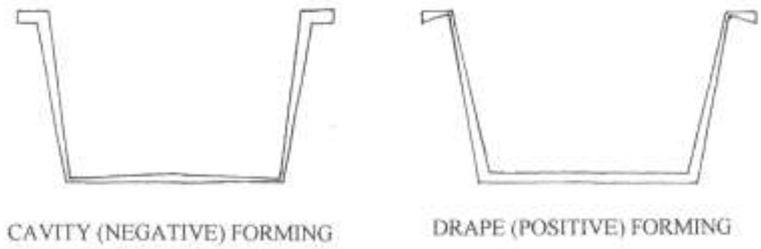


Figure 4. Drape Forming

As with cavity forming, the last area to form is the thinnest. This avoids thin corners at the bottom as occurs with Cavity Forming, but is thinner at the rim (figure 3) and prone to forming webs. Cooling shrinkage can impede part removal.

3.4 Variations to Avoid Excessive Thinning

3.4.1 Cavity Forming with Plug Assistance

(figure 5)

In this process, a central plug pushes the heat softened sheet into the cavity of the female mould, simulating the drape forming effect on wall thickness, and vacuum is then applied to suck the sheet against the female tool. Some slippage between hot sheet and plug may be required to achieve the required wall thickness uniformity, but the plug must be very smooth to avoid marking the sheet. (Paradoxically, hard felt is sometimes used)[(6)].

Figure 5. Cavity Forming with Plug Assistance

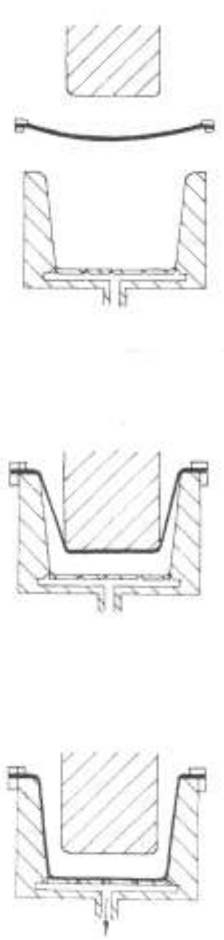
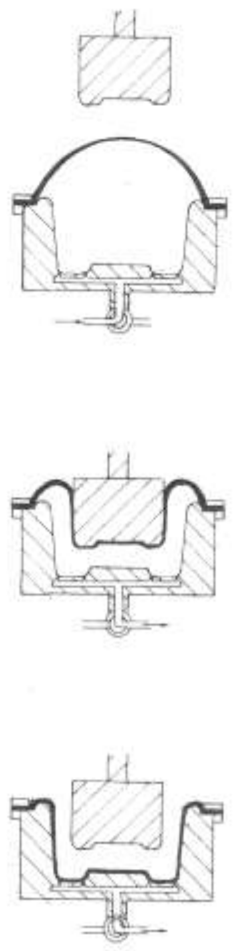


Figure 6. Billow Drape Forming



3.4.2 Billow Drape Forming

(figure 6)

A more uniform wall can also be obtained by inflating the sheet into a bubble as in free forming and then inverting this half bubble with a male tool. A final vacuum sucks the half bubble tightly on to the mandrel. A vacuum alternative is compressed air or both vacuum and compressed air.

3.4.3 Snap-Back Forming

(figure 7)

This is very similar to billow-drape but has the advantage of minimal drill marks, and the bubble need not be the full height of the male mould.
The sheet is drawn into a half bubble by vacuum, the male mould inserted and the sheet sucked back on to the male mould.

In a variation described by Gruenwald(5) and illustrated in the BPTA booklet(8), a half bubble is blown with compressed air, the male mould moves upwards into the half bubble and the sheet sucked on to the male mould.

3.4.4 Reverse Draw with Plug-Assist Forming

This uses the billow pre-stretching method with plug assistance in place of the male mould and vacuum forming into a female mould.

3.4.5 Twin Sheet Forming

(figure 8)

Twin sheet forming is a form of blow moulding but using two sheets instead of a hot tube between 2 mould halves.

Figure 7. Snap-Back Forming

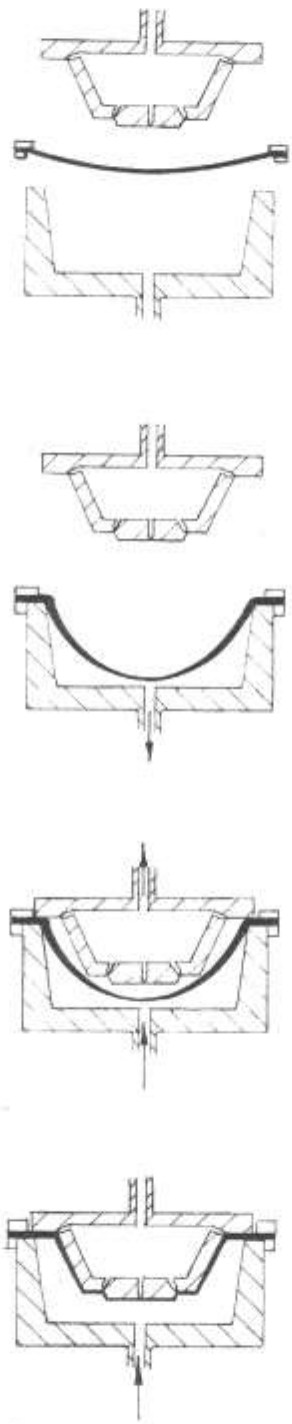
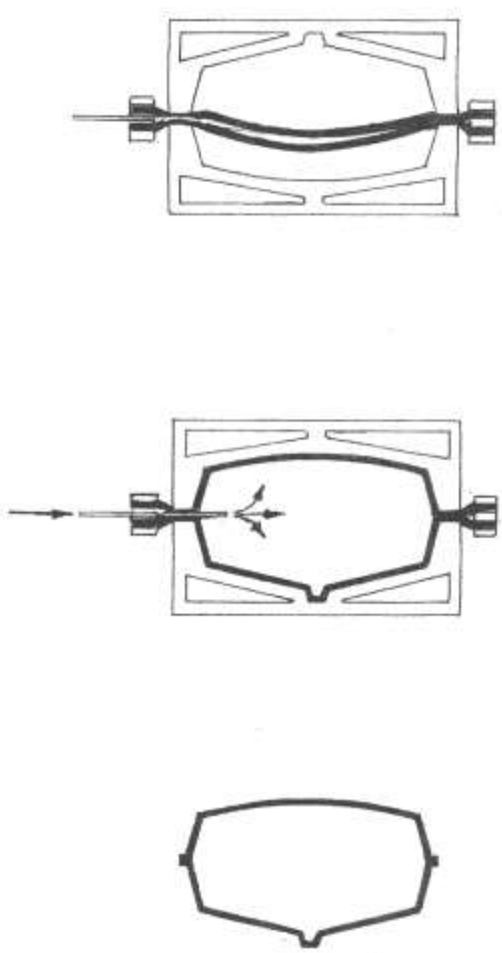


Figure 8. Twin Sheet Forming



As this is a more recent process compared with the other thermoforming techniques, this is described in more detail as follows:-

Twin sheet thermoforming according to Avery[3] had similar advantages over blow moulding as single sheet forming had over injection moulding, with added economic advantages of immediate colour and thickness changes. This technique also had product design flexibility such as different thicknesses between two sides, different materials with regard to colour, appearance, UV resistance, heat resistance, impact strength etc. and encapsulation of inserts for stiffening, and fixing.

E Galli[9] summarised the position of twin sheet forming. Twin sheet mouldings were normally selected because the double wall configuration maximises stiffness e.g. garage doors, pallets and containers. High molecular weight HDPE was often used as it held heat longer so enabling shaping of both sheets and welding together plus it had toughness to withstand knocks, common to many of the applications. Minimum sheet thickness was about 1.14 mm for HMWHDPE and 1.5 mm for ABS. Thermoformers normally extruded sheet to required thickness in-house and recycled trimmings and scrap.

Other than blow moulding, the other large rigid product manufacturing processes of structural foam, compression moulding and SMC, used more costly moulds than twin sheet forming.
Tooling for blow moulding and twin sheet thermoforming could be cast or fabricated aluminium with hardened inserts if necessary. Twin sheet tooling was up to 20% cheaper than equivalent blow moulding, but twin sheet was normally selected for features rather than cost. Its main advantage over blow moulding was size; up to 2.4 x 3.6 m. Stiffness was achieved by having many ribs on both surfaces with welded contact points.

Sheets could be formed sequentially to allow inserts, it could use filled sheets, different colours, different gauges. Plug assist was suitable only for sequential moulding.

Other polymers were used such as PC/PBT for form filled car bumpers, and Ultem (Polyetherimide) for aircraft ducting. Polycarbonate was used in aircraft at one quarter cost of welded aluminium.

Twin sheet forming needed correct alignment of 2 tools. Standard dowels and bushes were used (minimum of two). Pinch-off points and weld lines were designed in to bond sheets together and form a bead inside along weld lines. This also eliminated trimming and improved appearance. Venting, blow pin position and size, heating/cooling etc. were dependant on part design.

3.4.6 Other Techniques

There are many other variations in the text books listed in the references.[5,6,7,8]

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4. Tooling

4.1 Tooling Costs: Thermoforming versus Injection Moulding

According to Avery[3], trends towards shorter production runs resulting from more frequent changes in styling and needs to reduce development costs were creating thermoforming opportunities. Low volumes of 2 to 10,000 units were said to be more economic than injection moulding even though the starting material was extruded sheet.

The following data is taken from a table for comparative costs of pressure forming versus injection moulding for 1000 parts per year of an electronic equipment enclosure in Noryl.

Cost of thermoforming aluminium tool with trimming fixtures was $24,150.

Materials and thermoforming cost was $22.29 per unit.

The corresponding figures for a steel injection mould and materials and processing costs were $134,000 and $13.84 per unit.

Total unit cost including tool amortisation over 2 years was $34.37 for thermoforming and $80.84 for injection moulding, i.e. a thermoformed part would cost less than 50% of that made by injection moulding.

Avery's references were:
[13]Gabriele M C Mod. Plast. July 1996, 44 – 47.
[14]Schut J H (Ed) Plast. World May 1996, p29.

4.2 Tooling: Design Considerations

Unlike injection moulding, which needs close tolerance machining of matched steel die parts, stripper plates, ejectors and runners, thermoforming normally needs a single side to reproduce one side of the moulding. Consequently they are much easier to make[3].

A female mould cavity will be used to produce outside details and a male mould for inside details. No ejector pins are necessary. Injection mouldings normally require minimal if any further work prior to assembly, but thermoformed parts may require fixtures and jigs for trimming, machining holes, slots etc., although costs of these operations have been reduced by robot trimmers etc.[3]

4.2.1 Thermoforming Mould Design Criteria

To comply with the dimensional and thermal requirements of the Thermoforming process the following factors must be considered when selecting a material for mould making:

1. Must be capable of repeated thermal cycling,
2. Must be easily modifiable,
3. Must be able to transmit vacuum from all areas of its surface,
4. Must be robust,
5. Must be dimensionally accurate,
6. Must have a known shrinkage.

The reasons behind these requirements are:

1) Thermal Cycling: to maintain quality, dimensional stability and to avoid brittleness and moulded-in stresses the temperature of the mould must be controlled within a narrow range. To achieve this (and to avoid extended cycle times) the mould material must have excellent thermal performance.
2) Design Changes: the thermoforming process offers fast turn-around and low volumes – this results in frequent design (and hence mould) changes. One report claimed that 30% of designs are changed during the mould-making phase.
3) In most applications the vacuum holes must be as small as possible. The practicalities of drilling very small holes into a mould affects the selection of mould materials and shell thickness.
4) Robustness can be achieved through the inherent strength of the material or its thickness (but this has an effect on 3).
5) The plastic will replicate the mould dimensions so design of the mould must recognise the materials shrinkage and that of the plastic.

Tooling details have been recommended as follows[3]:-

Standard practice:	Specify either minimum wall thickness or sheet thickness.
Stretch ratio:	Ratio of part surface area to original sheet area. Pressure forming – max 3:1, average 2:1 or less.
Draw ratio:	Ratio of maximum mould depth to minimum across open mould face at given location. For pressure forming <1:1 considered best.

(Note: geometries treated in more detail in section 6.2).

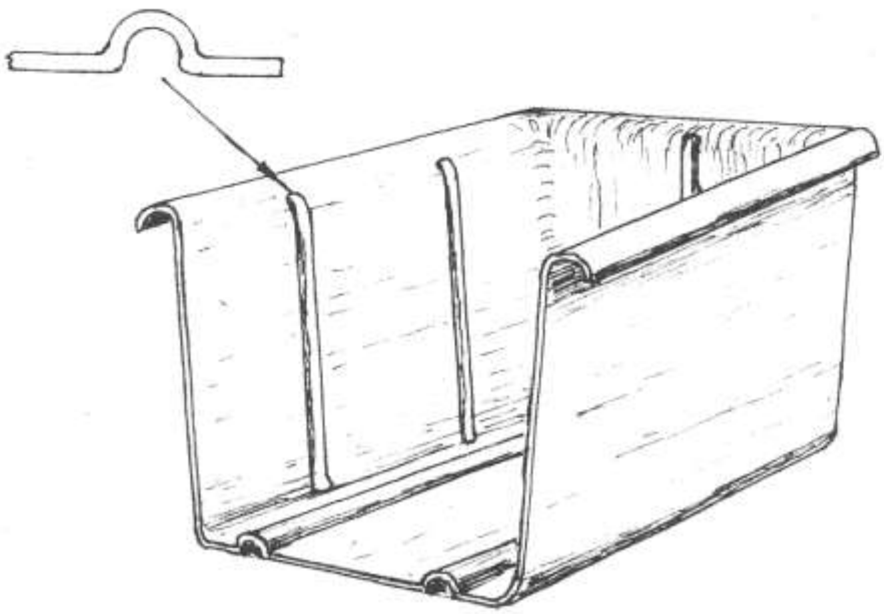
1) Ribs: (figure 9)

Solid ribs not possible.

For stiffening:

- Female mould; outside rib width minimum 1.75 x rib depth.
- Pressure forming; minimum distance between ribs = rib height.
- Thick walls may require wider ribs.
- High pressure forming gives sharp detail; rib width can be 1 – 2 x wall thickness (see figure 9).

Figure 9. Cavity Moulding Rib Design



Outside rib width minimum 1.75 x rib depth
Thick walls require wider ribs
Pressure forming: minimum distance between ribs = height
High Pressure forming: rib width can be 1-2 x wall thickness

2) Undercuts:

These are used for locations and snap fits. They normally have large radii and smooth contours. In pressure forming, moving cores can form 12.5 mm deep undercuts (or deeper with special tooling). Examples of undercut tooling are shown in the books by Gruenwald[5] and Illig[7].

3) Tolerances:

Avery's table[3] gives tolerances for pressure forming only. (Presumably from his reference; Beall G. Design Guide II for Pressure Formed Plastic Parts, distributed by Arrem Plastics Inc. (Addison IL).

- General: ± 0.030 (presumably in inches i.e. 0.76 mm)
- Drilled holes CL to CL: ± 0.020 (0.5 mm)
- Computer machining: ± 0.020 (0.5 mm)

4) Draft (taper):

A taper is needed for part removal.

Male moulds:	3° minimum
Female moulds:	1° for smooth tool surface
	1° of draft for every 0.025 mm of texture depth

5) Basic Considerations:

- Which side of the part contains the detail?
- At what locations are tolerances required?
- Are different parts assembled and must they fit together
- Male moulds are less expensive than female moulds
- Are "matched" moulds required

6) Trimming:

For economy, edge trim should all be in the same plane. To achieve tolerances, trimming should be carried out after all post moulding shrinkage has occurred. An example is given of an ABS part 1.2 m wide changing 1.8 mm due to a 5°C difference in temperature. CNC milling, high-pressure water jets and lasers can be used.

4.3 Heat Transfer Considerations

For thin gauge sheet Throne [7] states that the mould surface temperature should be above the temperature at which in-mould condensation can occur. Condensation causes dimples in the walls of formed parts.

For heavy gauge sheet Throne [7] states that the mould surface should be ca. 5°C below the Glass Transition Temperature (Tg), the Heat Distortion Temperature or the recrystallization temperature of the polymer.

For low volume or prototype applications where cycle times are of less importance the mould can be constructed from materials such as Resin, Plaster or Wood. The thermal properties of these materials do not permit accurate control of mould surface temperature and frequently the mould temperatures are significantly lower than the ideals stated above. Although low mould surface temperatures decrease cycle times, excessive residual stresses are locked into the formed parts under these conditions.

Some of the stresses may be relieved during trimming, when the product is stored at elevated temperatures, during shipment, or in use. These stresses can result in a deformed or distorted part. Mould surface temperatures should be high if replication of the mould surface of the sheet is required – e.g. in pressure forming off a textured mould.

4.3.1 Mould Temperature Control

Channels within the mould or bolster plates are normally used to add and remove heat from the mould. Water is the most common cooling medium because it is efficient in adding or removing heat. For higher temperature moulding where the mould temperature has to be maintained above 80-90°C it is safer to use Hot Oil. And it is not uncommon to add cartridge heaters to moulds for parts with difficult designs.

To achieve uniform heat transfer across the mould surface it is imperative that the fluid has turbulent flow everywhere in the coolant channel, regardless of the fluid used. To achieve turbulence water should be flowing at least 0.34m/s in 25mm internal diameter lines and 0.7m/s in 13mm internal diameter lines. Typically, Thermal Oil has higher viscosity and lower density than water and, as a result, must flow faster to remain turbulent.

Temperature across the mould surface should vary by no more than 1°C and the fluid temperature rise should be no more than 3ºC. Part-to-part non uniformity in thin gauge multicavity moulding and warping and side-distortion in heavy-gauge moulding are frequently directly attributable to non-uniform mould surface temperature.

4.4 Tooling Materials

In a review of rapid prototyping in general but which tends not surprisingly to be biased towards injection moulding, the author[10] quoted a consultant who divided the techniques into "additive" and "subtractive". Additive tooling used techniques such as stereolithography while subtractive used material removed by CNC techniques.

The many additive techniques were more easily applied to thermoforming as only one mould piece was needed, and it did not need to exactly mate with a second piece to form a cavity and stresses involved were comparatively low. As the wall thickness of vacuum formings were (by the nature of the process) variable, the lesser precision of additive tooling compared with subtractive would normally not be a problem. For subtractive prototyping, aluminium or aluminium filled epoxy was normally used.

In a table comparing 5 different tooling techniques, the additive methods lead times tended to be 1 to 2 weeks and CNC machined aluminium 4 weeks. The overall situation at this date (May/June 1998) was that all the systems compared benefited from CAD to produce relatively accurate tooling of reasonable durability in a comparatively short time. Not mentioned was what remedial actions, (if any), were possible if design changes proved necessary.

For many years prior to CAD/CAM and stereolithography techniques, moulds were either hand made or replicated using casting and hand laminating techniques from hand fabricated/semi machined materials. These techniques may still be the only practical way of producing prototypes and short runs in some circumstances, particularly for large components.

R Harris(11) produced a book in 1973 which includes details of producing thermoforming tools from wood, plaster, epoxy and polyester resins, fablite, and sprayed metal without CAM and rapid prototyping. The starting point was the skilled pattern maker.

The criteria to be met were:-

1) The labour and materials cost should be low.
2) Modifications to the mould should be possible for design changes.
3) The mould must not deflect or deform during moulding.
4) The mould must withstand 65 to 93°C.
5) Part appearance must be acceptable.

It was emphasised that ease of alterations could save time and money should revisions be necessary.

Avery(3) divided tooling materials into 3 categories:

Material		Applications
1)	Hardwood	Prototypes and pilot runs
2)	Filled epoxy	Low volume production
3)	Aluminium (cast or machined)	Full production

Steel was not mentioned. It should be noted that Avery excluded high speed thin sheet packaging from his book presumably as this was outside his remit. He stated that aluminium was used not only for its durability, but good thermal conductivity combined with heating/cooling channels minimised moulding cycles. Illig[6] stated that aluminium was the preferred material for thermoforming tools. The advantages of aluminium were its good heat conductivity and ease of machining.
The advantages of aluminium are its good heat conductivity and ease of machining. Thermal conductivity data for various potential tooling materials are given below.

Tooling Material	Thermal conductivity (10^{-3} kw/m °C)
Aluminium	124
Resin	1.3
Plaster	0.298
Wood	0.125

Table 1: Tooling Conductivity Data

As can be seen aluminium conducts heat 1,000 times better than wood and 100 times better than a typical resin. Metals are conductors, whereas polymer based materials are thermal insulators.

Therefore, aluminium because of its cheapness, availability and the highest thermal conductivity of all common mould materials is the preferred material for production moulds.

Aluminium moulds can be cast or machined, or a combination of both. Temperature control piping can be cast into the mould, fixed to the inner wall of the mould or bored in machined moulds. The strength of the metal allows moulds to be made with a 25mm wall thickness to give the robustness, short vacuum holes and a vacuum chamber.

Prototype moulds and moulds for low volume applications are usually fabricated from more easily worked materials such as resins or composite materials.

If the utilisation of filled resins and composites is small, then there is a surprising number of different brands described in editorial review type journal articles. This might be explained by Illig's statement, that "due to the various areas of application and the different versions of thermoforming machines available, specialist tool making branches have evolved over the years".

4.1.1 Wood

According to Harris[11] kiln-dried hardwoods such as birch, maple and mahogany are the most common varieties used. Mahogany was considered easier to machine and glue, but all woods changed dimensions with humidity if not sealed with suitable varnish. Insulating properties would result in heat build up and forming halted by lack of cooling. Conversely, plug assist benefited from heat build up. Details of jointing, producing inside radii, countersinking screws, end grain problems etc. were dealt with.

Throne[7] covered similar points but also rated 7 species on a 0 to 100 scale for planning, shaping, drilling, sanding and resistance to splitting. Whilst maple, birch and mahogany were commonly used according to Harris, Throne's table shows maple poor for sanding 30-39 and mahogany with 40-49 rating for shaping and resistance to splitting, with no mention of birch. Ash rates well except for shaping at 50-59.

Vent holes were usually drilled through the primary surface first and counter bored with larger holes from the back. Epoxy enamels and varnishes were said to give sufficient protection for hundreds of cycles, but softer bands within the wood grain could result in unacceptable texture from preferential shrinkage. Throne also tabulated mechanical properties of a number of woods (excluding mahogany).

4.4.2 Plaster

According to Harris[11], in most cases, plasters needed replication from a model or pattern. Unlike other mould making materials, plaster expanded, a property which might be used to offset moulding shrinkage. Being fragile, plaster needed careful mounting, whilst fibres or wire mesh reinforcement could be used. Procedures for casting male and female moulds were described. Vacuum holes could be formed by placing fine piano wires in position and withdrawing with pliers after cure.

Throne[7] considered most commercial moulding plasters were not strong or tough enough but a table was given of setting times and compression strengths for five moulding plasters. "Splatting" a thin layer of high water content plaster on the mould pattern surface produced a very hard void free finish to the plaster mould. An optimum water content was needed in the mix to achieve good physical strength whilst avoiding air bubbles and voids. The process is exothermic and drying for several days may be required. Although durable and able to withstand cyclic forming temperatures, when they do break they are not worth repairing and a new mould will be cast from the pattern.

4.4.3 Sprayed Metal Alloys

Excellent surface detail could be replicated by spraying low melting point alloys against a pattern[(12)]. These tools were suitable for full production as well as prototypes. It was sprayed much like paint. As there is no heat build up in the pattern, many materials including plastics can be used for the pattern. Once a surface of 1.6mm to 3.2mm has been deposited, the back can be filled with epoxy/aluminium and other materials described below. As with plaster and cast epoxy resin based materials, piano wire can be used to form vent holes. When the tool is no longer required, the metal can be re-used.

4.4.4 Resin Tooling

Thermosetting liquid resins for thermoform tooling get regular mention, mainly in superficial review articles, which make their relative technical merits difficult to assess. Although there are far more references to resin composite tooling than aluminium tools, to quote Illig[(6)]; "aluminium-resin combinations are rarely used".

In general, tools using resins appear to fall into two categories although not formally described as such:

1. Large moulds in which techniques resembling GRP boat building are used with hand lay-up or spraying using fibre reinforcements, plywood stiffening etc.
2. Smaller moulds where filled resins are either cast or machined.

For large moulds, polyester resins are frequently used, as material costs are lower and glass fibre reinforcement is readily incorporated. The fabrication of polyester-glass fibre tools, which is described in detail by Throne[(7)] and Harris[(11)] although similar to boat building may require considerable stiffening to withstand the comparatively high loads imposed by 1 atmosphere over a large area. Epoxy resins, which have superior heat resistance to polyester resins, can be used, although more expensive and harder to fabricate.

An article by Reimann[(12)] covers use of synthetic resins for a wide range of tooling applications including sheet metal forming and foundry work, but includes plastics processing.

1) **Polyurethanes:** These varied from rigid to flexible; fast curing reactions were possible and they had resistance to wear and abrasion.

2) **Methacrylates:** They had high flowability, fast curing reactions and thermal resistance.

3) **Silicone polymers:** They had self-releasing properties, high elongation, easy demoulding and high thermal stability.

4) **PMMA casting resins:** When filled with high levels of aluminium powder they offered fast processing, fast curing, and good machinability. Large moulds had shown good performance in many years production. Heat shrinkage during curing could be a problem.

5) **Epoxy Resins:** These were used for dimensional stability, mechanical strength, thermal stability and adhesion to fabrics and fillers. Previously Epoxy Resin tools were restricted in temperature performance (max 125^{O}C) but new resins claim to be able to withstand much higher temperatures.

Modern Aluminium-filled casting resins can be supplied in liquid form and are typically ready for finishing within 48 hours. Although the product literature claims "good thermal conductivity" there is no data to make a reliable comparison with Aluminium. Cooling channels can be cast into the Resin but must be located close to the surface. Problems may arise if the design of the product has to be changed. Removal of resin can be easy but addition of resin may be difficult. Care must be taken to ensure that identical resins are used to avoid differential expansion. Adhesion of the additional areas may be difficult.

By using an equal weight of several layers of glass cloth with a specially formulated heat resistant resin, moulds of high accuracy, heat resistance and thermal stability can be achieved. A 30 – 50 mm back-up uses a mixture of resin and aluminium granules.

Nowak(13) divided thermoforming mould materials for models and prototypes into "direct methods" and "indirect methods". An example of the direct method was to make a male model in polyurethane foam, seal with a filler and then spray a zinc/tin alloy to a 0.5 – 1.0 mm thickness by flame spraying. The surface was then rough sanded. The tool shape could be modified by sanding and/or adding filler.

In the indirect method, an impression of an initial model was used to form a male or female mould. Brittleness of gypsum and embedding compounds under thermal loads limited their use to intermediate models. The surface layer applied to a model could be a polyester or epoxy resin containing slate or aluminium filler to give a 50 mm thickness. 2 mm slate platelets gave a porous layer, making drilled holes unnecessary, unlike moulds of wood, aluminium, zinc, brass or steel. This was in 1980.

4.4.5 Aluminium

Illig[6], Gruenwald[5] and Avery[3] considered aluminium to be the primary material for production tools. It can be used (cast or machined) not only for its durability but good thermal conductivity combined with heating/cooling channels that minimises moulding cycles. Steel inserts can be used for clamping and other areas requiring increased hardness. Aluminium is also suitable for higher pressures in sheet pressure forming and twin sheet forming. As more design work uses CAD, machining has become more popular as CAD can be directly transferred to CNC machining equipment. This also allows it to be used economically for small test tools. Sand or ceramic precision casting should only be used for aluminium tools in those cases, where machining proves uneconomical, but even so, a machined pattern could be the starting point. Aluminium is an easy machining material and higher specifications for strength are available from certain alloys. Shot peening of cast aluminium tools eliminates surface porosity. It is also suitable for the higher stresses in sheet pressure forming and twin sheet forming.

4.4.6 Steel

Nothing was found on the use of steel for thermoforming moulds. Davis[14] gave a very comprehensive review of steel and alloys for mould tools, but this was essentially for compression and injection moulding.

4.4.7 Russian Tooling Practice

An article by Sheryshaev[15] covered similar ground to Harris[11] and Throne[7] but is included as a separate item as although the translation is difficult in places to understand, it contains a number of points which were not found elsewhere.

There is some extra detail on plaster moulds which covers influence of drying times and temperatures on durability. Curing was also said to be improved by impregnation with 30% iron or copper vitriol solution and also with a weak liquid glass solution. As non-impregnated plaster moulds are porous, evacuation holes need to be provided only where the most intense suction is needed.

Cooling of cast polymer moulds can be by a “cooling jacket” which also reinforces. In more complex geometry moulds, cooling is by a small metal tubing coil 6 – 10 mm from the mould edge, wired in position during casting.

A process of “stone casting”, which is similar to cast resin and ready after 30 hours requires no additional treatment. Vacuum holes are provided by wires removed after 14 hours of the 30 hours hardening time but metal reinforcements need protection against corrosion. Glass fibres can be used. Coils within the mass can also be used to remove heat released during curing.

In addition to metal moulds, electroplated concrete moulds can be used for prolonged service. They were described as consisting of a thin-walled moulding marker/shell, which is placed in a metal casing and flooded with a non-metallic support e.g. concrete. A full description was given of what appears to be an electro-deposited metal replicate backed with concrete. An odd assortment of materials including lacquered paper-maché were also mentioned.

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5. Proprietary resins and resin based materials for tooling

These are mostly epoxy based as having the best heat resistance. The earliest proprietary material described specifically for thermoforming covered by the computer limited search period was the 1973 article by Harris(11) , but epoxy based jig and tooling materials were used for engineering purposes long before then.

5.1 Axson EPO 4042 EPO4042/L Epoxy Casting Resin

This is an aluminum-filled two-part epoxy casting resin for vacuum-form tools. Midas patterns report that it is a good casting system, offering good temperature resistance and edge strength. The system needs a master pattern in order to cast the vacuum. The material is stable and long lasting, ideal for low - medium volume runs (100 - 2000 off). A data sheet is provided in the appendix.

5.2 Epon Epoxy Resins

According to Harris(11), castable resins were widely used for thermoforming tooling and a two impression aluminium-filled epoxy mould and thermoforming are illustrated. The resins (usually epoxy) were well filled with aluminium to improve thermal conductivity and hence cycle time. A model or pattern was normally required.

Details of making a mould using resins were given. As materials were not inexpensive and large moulds could be heavy, they were frequently filled with a porous backing which also simplified the provision of vacuum holes.

The surface coat was aluminium filled resin applied to a thickness of 2.54 to 3.175 mm. The rest of the pattern was filled with epoxy coated aluminium needles, not packed tightly but tamped lightly so that the voids between needles were interconnected, making the filler porous. The vacuum holes were drilled through the surface coat in the required places.

The aluminium-filled epoxies were readily available from many well-known suppliers. A premixed aluminium needle-epoxy package was available but required a 177°C cure temperature. Alternatively a room temperature curing mix could be prepared as follows:-

Epon 815 epoxy resin	200 g
Shell T-1 curing agent	50 g

Aluminium needles	2000 g

The needles were coated just sufficiently to stick together.

5.3 Fablite

According to Harris(11), Fablite Incorporated of Romeo Michigan, granted licences to make moulds by its patented process (which will have expired by now) to produce porous tools which had no need for vent holes. A filler such as aluminium powder was mixed with the Fablite binder (material undisclosed) and used to make a mould in a similar manner to the epoxy system. The cure cycle involved 5 steps which volatilised excess resin leaving a permeable to air surface coating.

As with the epoxy moulds, the Fablite mix could be confined to the surface, which sped up the forming cycle, and the rest of the mould filled with an aluminium grain and resin combination.

5.4 Polylite Polyester Resin

In work reported by Brooks and Walsh(16) to predict mould surface temperature using an FEA model, the mould used was made from a filled Polylite 33540 – 00 zero shrink mass cast tooling resin. The material composition was 50% aluminium powder and 35% aluminium pellets in zero shrink polyester resin. The aluminium increased thermal conductivity from 0.17 to 3.36 w/mk. Heat capacity was 1050 J/Kg K and density 2110 kg/m^3.

5.5 Metapor Epoxy/Aluminium

Knights(17) reviewed thermoform tooling using porous material from Portec produced since 1995. It consisted of 65 – 90% aluminium powder, 10 – 35% epoxy resin and had 15% voids. Its surface had pores of 15 – 16 microns diameter. It was used for prototypes, production moulds and cavity inserts. It was supplied in machinable blocks or castable material called Espor (see 4.5) and used with most plastics for thin gauge packaging, fridge door liners and automobile dashboards.

It was said to reduce lead times as elimination of drilled surface holes reduced CAD and machining times. The porosity gave faster cycles from faster draw, and cooling starting sooner. Plug assist sometimes became unnecessary. With some tools the drawn air provided all the necessary cooling which made it particularly attractive for prototype tooling.

Being polishable to 200 grit, although not to the potential surface finish of aluminium, it could give high detail or optical quality without marring surface. (In any case highly polished tools could make demoulding difficult). It was suitable for large flat products free from vent marks and surface imperfections, and there would be no

“lakes” or “wave effects” from air trapping. Transparent polyolefines could be high gloss sheet with no scuffing due to sliding. It also gave fine surface detail such as leather grains, lettering etc. and also saved time by eliminating drilling holes for fine details.

The porous material enabled unusual shapes to be made where otherwise vent locations would be extremely difficult to drill.

Disadvantages were that plates greater than 100 mm thick reduced air flow rate due to increased pressure drop and cooling temperature gradient became too large. For deep moulds, hollow box sections of thin slabs joined with epoxy resin were recommended.

Vacuum ports required attention to get uniform draw, and vacuum channels were arranged in a grid pattern on the back of the mould. Portec suggested a 300 x 406 x 38 mm mould should use vacuum distribution channels 15 mm wide x 5 mm deep, 50 mm apart. Main vacuum pipe should be mounted centrally to prevent out of balance draw.

CNC machining was recommended but the epoxy limited use of EPM and polishing could reduce porosity by partial pore blocking.

The pores were so small that blockage was not a problem and any contaminant could be blown back. Repairs were possible.

The material was softer than standard aluminium but had been used for 1.6 to 5 million parts. It was used for decorative inserts for cell phones etc. where vent marks must be avoided.

Material costs were twice that of 6061 aluminium. It was produced in 500 x 500 mm slabs 10 to 400 mm thick. A standard 500 x 500 mm slab would be needed for a 150 x 100 x 50 mm mould and would cost $750 (in 2001). Price could be reduced by confining use to inserts.

Savings on machining depended on tooling e.g. multiple cavities requiring many vents with solid tooling would be economic. Normal temperature limitation was 108°C but high temperature epoxy allowed 210°C. Metapor HD210 had improved heat resistance for forming polypropylene and acrylics. "Protoblack" was produced for cost effective prototype tooling.

5.6 Espor

For textured deep-draw detailed moulds e.g. for automotive applications a castable version of Metapor called "Espor" could be used. R L Bowen[(18)] described some of its uses. A pattern made of wood, epoxy, or any rigid material could be replicated. Espor was mixed and poured with in-situ cooling pipes as required and strengthening ribs as needed if a typical aluminium shell type tool was made. When set, excess material was milled off, the tool "squared up" and cured.

A long list of advantages was included as follows:-

- No size limit.
- Good texture detail.
- 36% lighter than aluminium.
- Rapid tooling.
- Shrinkage only 0.01%.
- Wear resistance as good as aluminium.
- Undercuts possible (with slides).
- Can be cleaned with soap and water and reverse blow dried.

No costs or disadvantages were included.

5.7 Vestalloy

Included in a review by Tolinski[(19)]. Made by Matrix Composites LC USA.

A metal filled vinyl ester compound said to retain its properties at most thermoplastics processing temperatures. It contained "uniquely configured" filler particles to provide good thermal properties. It was said to perform well in thermoforming as well as RIM, compression and foam in place moulding. Injection moulding was being investigated as it had excellent cohesive strength and withstood temperatures up to 260°C. Compared with standard epoxies, it had about 20% higher wear resistance, at least double thermal conductivity and better machinability than standard materials. The article's table rates wear resistance and dimensional accuracy to be similar to aluminium.

5.8 WIS Tooling

This technology by Cubital America Incorporated (also in Tolinski's review[19]) produced aluminium filled epoxy tools from a prototype part made by UV curing successive layers of a special photopolymer. A temporary wax support was used during replication; termed the "wax-in shell" (or WIS) method. Tolinski's table rated wear resistance less than Vestalloy and gave tool life as <1000 parts.

5.9 Albright RT

Albright Technologies Incorporated RT[19] was not a composite in the filled resin sense, but a two component tool used for injection moulding in which a cast room temperature vulcanising silicone rubber was supported within rough machined cavities in an aluminium support. The silicone insert was cast from a stereolithography pattern and when excessively worn, e.g. after 1500 mouldings, the insert could be replaced with a new silicone insert.

5.10 Poly Steel

Devised by Dynamic Tooling (USA), Poly Steel is a 90% steel filled epoxy said to be 400% stronger than aluminium filled epoxy[19]. Using stereolithography patterns, accuracy was better than 2 rms surface finish and 0.001 mm/mm of the SL model as expected by motor industry customers. It was said to be suitable for injection moulding 30% glass filled nylons at 300°C without degrading or wearing. Tolinski's table[19] rated heat transfer similar to aluminium epoxy but wear resistance and dimensional accuracy rated better and tool life given as 100,000 + parts.

5.11 Microsyn

There is brief mention in a summary of an SPE Thermoforming conference presentation [20] on Microsyn two part epoxy based Syntactic foam. (Matrix Asia Pacific).

1) Ambient cure system
2) Resistant to 120°C
3) Designed for large castings
4) Can be used in conjunction with "microballoons"
5) Low thermal conductivity prevents overheating of moulds

(note: not obvious why this should be)

Used for 3 mm ABS sheet with a sheet temperature of 200°C.

5.12 Ren-Shape (Vantico)

Ren-Shape 5008 board from Vantico[21] can be used for making prototypes and short run mould bases or cavities. Ren-Weld 5008 adhesive is used for bonding boards, together with Ren-Patch repair paste.

Mills Manufacturing in Oregon used Ren-Shape epoxy laminating system Ren RP 4005/RP 1510H for tools to thermoform 6.5 mm polycarbonate mouldings to protect luxury motor homes from rocks and other road debris. Tools were moulded vertically against the actual vehicles.[22]

Knights[23] (editor) gave some details on Vantage Tool and Engineering's manufacture of low cost thermoforming moulds using Ren-Shape type 450 board. This was a filled polyurethane having a glass transition temperature of 96 ^{0}C, Shore hardness 65D and tensile strength 160Kg/cm^{2}. The boards were 100mm thick, size 0.406x1.25m several boards were laminated together as required with Ren-Weld 103 adhesive, enabling cavities with up to 600mm depth of draw to be made.

Typical mould manufacturing time was 3 days compared with 2 weeks for aluminium. A small Ren-Shape mould of 300 x 300mm could be made in a day.

Machining practice developed by VTE was to use two fluted hardened steel ball-end mills at 3500 rpm and 3.27m/min rough cutting, beginning with an 12.5mm deep cut, followed by 25mm cuts and then 40mm deep cuts. Finishing cuts were made with 6.5mm tapered, fluted end mills at 4500-5000 rpm and 0.38-4.0m/min, using 0.178mm stepover to produce mould surfaces requiring no secondary finishing. (Note: e-mail from Huntsman (Europe) suggested BM5055 board data-sheet, (see in appendix), would have similar machining properties).

The finished cavity was inserted into a standard aluminium mould base. As heat built up may damage the tool, with thin sheet thermoforming the tool must be allowed to cool after a few mouldings. However with heavy gauge sheet, the tools heat retention gives good part definition and the slow cycles allow up to 500 heavy gauge parts to be made, whereas with thin gauge the limit may be 50 cycles.

Ren-Shape moulds up to 1.5 x 1.8m were used to form a truck cab's dashboard, interior, roof, fridge, stove and bunk.

5.13 Polyurethane Machinable Slab (Ureol Board Axson)

Materials are available in different densities.

Lab 1001 from Axson is described as a Tooling Board; with applications in checking fixtures. It is available in 50mm and 100mm thicknesses and can be adhesive bonded. It has an SG of 1.60 g/cm^3.

Prolab 65 from Axson is designed for the production of patterns, mock-ups, prototypes and masters by milling or machining by hand. Slabs are available in various sheet sizes in 30mm, 50mm, 75mm and 100mm thicknesses. They can be bonded together adhesive or mastic. Slab density is typically 0.6g/cm^3 with a Shore D1 of 63.

These materials were identified by Midas patterns and data sheets are included in the appendix.

5.14 Epoxy / Aluminium using Stereolithography (Escuelo Technica)

A well illustrated and detailed article by P Lafont Margodo and G Garcia Martinez de Saleras (in Spanish) described the manufacture of a tool in 70% aluminium powder and 30% epoxy resin EP250 using stereolithography. Heat distortion temperature was 250C. (24)

5.15 Miscellaneous Materials

A number of materials are briefly described in press releases and summaries with little if any technical information. From the technical press articles, these products are often used with stereolithography but it is not always clear whether for a prototype, a master for replication, or the tool itself. In many cases the intended moulding technique is vague with thermoforming as an afterthought.

Articles appearing over the last 10 years which appear from their abstract to have reasonable evidence of their suitability for thermoforming tooling are summarised as follows:-

1) Axson (France) epoxy/PU. The fast setting epoxy/PU.F50 can be used to produce models, prototypes or production tools requiring very thick castings. [25]

2) 3D Systems and Ciba Speciality Chemicals supply Cibatool SL 5530 HT epoxy which was used with stereolithography to produce vacuum formed 0.6 x 1.5m polycarbonate shield for Bell Augusta tail rotor. The tool withstands 200°C. [26]

3) (In Spanish). A selective laser sintering (SLS) 2000 service is offered by AIJU for plastics prototypes and moulds [27].

4) (In Spanish). The types of moulds which can be produced by MCP metal spraying are discussed [28].

5) T2L Chimie of France is a Ciba Speciality Chemicals subsidiary supplying thermoset casting resins[29].

6) Cibatool PU tooling board BM 5185[30] can be used as a replacement for hardwoods. Ureol J146A/B is a two-component Polyurethane mass casting system. Araldite epoxy tooling paste applied in layers by a dispenser gives a seamless wood-like finish.

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6. Tooling: plug assistance

6.1 Plug Assisted Thermoforming

Ayhan and Zhang[2] in their introduction considered the non-uniform wall thickness and the thinning at container bases were the most significant thermoforming limitation. This was caused by the heat softened sheet not contacting the mould surface at the same time but in sequence. As the wall formed last is the thinnest, a female mould will produce containers with thick rims and thin bottoms, and a male mould will produce the opposite. (figure 3) Among the various techniques employed to produce more uniform wall thicknesses was a female mould combined with plug assistance pre-stretching. (see section 2.4.1 and figure 5). This enabled the moulding wall thickness to be increased in load bearing regions. However, thickness distribution was never uniform. Aroujalian et al[31] were cited as showing that wall location, plug temperature, plug velocity and their interactions influence wall thickness.

Illig[6] considered plug assistance was necessary to prevent excessive thinning at the bottom of female formings when depth was greater than 3 times opening width/diameter.

The operating sequence is as follows (figure 5).

1. The sheet is heated to the forming temperature.
2. The female forming tool moves up and the plug simultaneously moves down, stretching the sheet mainly at the sides.
3. When mould and plug movements are completed, vacuum is applied, (and/or optional positive air pressure from above).
4. Plug retracts.
5. When cooling completed, forming is ejected. (It appears to be used mainly in the thermoforming of thin wall packaging). Thickness at the thermoformings base can be increased by enlarging the plug to minimise the space between it and the mould and by advancing the plug movement relative to the mould.

The plug requirements are as follows:

1. Chilling of hot sheet must be avoided otherwise sheet will not be drawn uniformly against the tool.
2. Surface must allow hot plastic sheet to slide.
3. It must be mechanically sufficiently robust.

4. It must have adequate heat resistance.
5. It must be easy to machine and produce at economic cost.

In a table covering an extremely wide range of thermoformable materials, four or more of the seven listed materials could be used. These were laminated wood, nylon 6, polyurethane-talc, felt, hollow glass spheres/epoxy syntactic foam, “Pertinax” and Acetal.

Aroujalian et al[(31)], carried out experiments of a practical nature to determine the influence of plug velocity and sheet temperature on wall thickness variations and average wall thickness in vacuum formed strawberry containers using HIPS sheet 0.34 mm thick. Sheet/film temperatures of 118, 125, 136, 150 and 165°C, and plug velocities of 0.15, 0.20, and 0.27 m/s were used with plug temperatures of 25, 60, 100, 123 and 125°C. The female aluminium mould was at 25°C. The square mould with radiused corners was 100 x 100 mm at the top, 80 x 80 mm at the base and 70 mm high. A drawing of the plug was shown, top 82 x 82 mm, bottom 69 x 69 mm and height 67 mm. The metallic plug (material not specified, but probably aluminium) was heated, and temperature controlled using 4 electric pencil elements.

Data for 0.15 m/s plug velocity and plug temperatures of 25 and 60°C were not included as forming was incomplete following sheet chilling by the plug. Graphs of wall thickness at 10 mm height increments from bottom to top showed a steady fall from lip to base with no plug, and a reasonably consistent value from 10 mm below tip (approximate thickness of sheet) to base for plug assistance. (Report figure 10 reproduces Aroujalian et al. figures 1 and 2 from reference [(3)]).

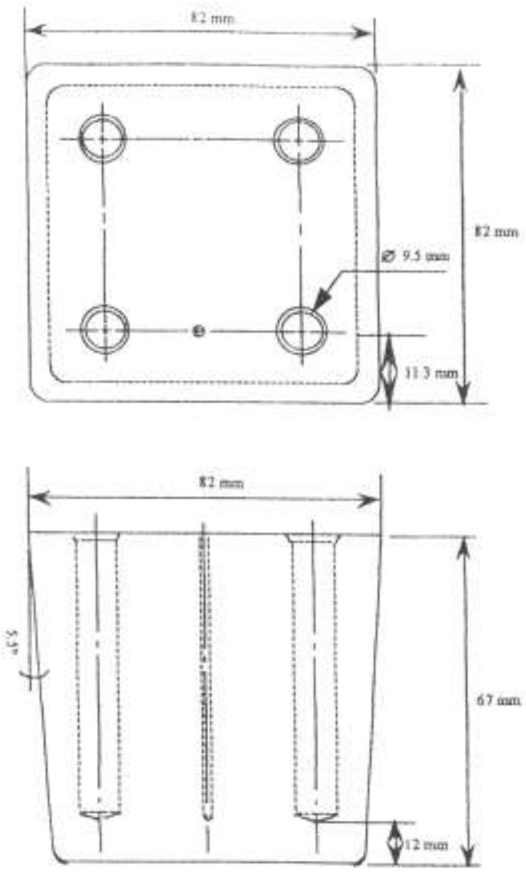
The highest mean wall thicknesses were obtained at optimum plug temperature range of 100 – 123°C, and plug velocities of 0.15 and 0.27 m/s. Minimum wall thickness variations were obtained at the highest plug speed (0.27 m/s) and lowest plug temperatures (25 and 60°C). Reference was made to Shih[(32)] who made similar observations for APET. More uniform wall distribution was achieved from elastic high speed deformation obtained with reduced stretching time and reduced heat loss from sheet to plug.

In a paper on the influence of film temperature on wall thickness the reviewing background preamble by Poller and Michaeli[(33)] mentions that the parameters of orientation and crystallisation can be readily changed only by controlling heating and cooling as moulding geometry is specified. However, if changes to the tooling appear necessary, the plug will be attended to first as this entails lower costs than attention to the mould.

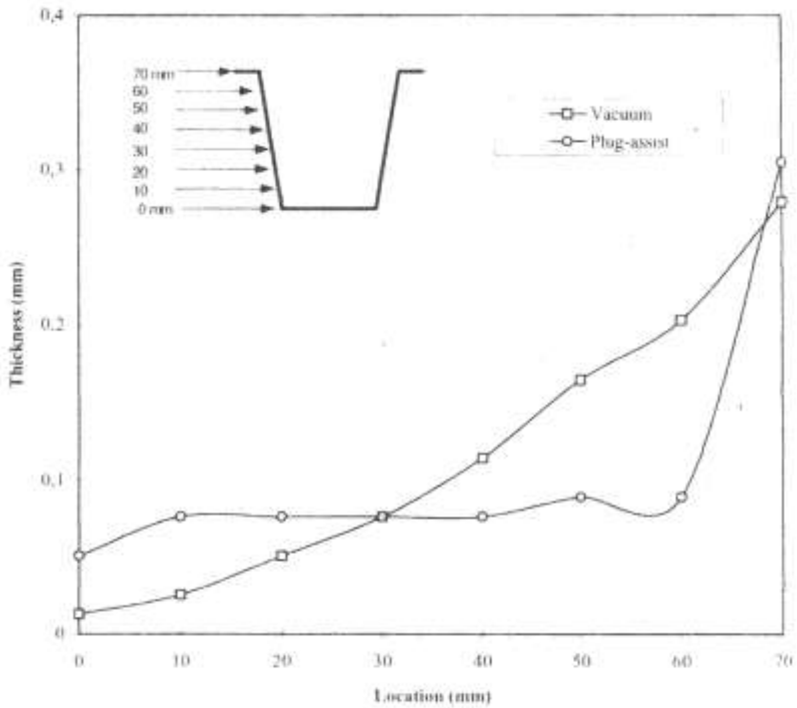
6.2 Plug Materials

As described in section 5.1 the thinning at the corners of parts formed in female moulds can be reduced by using an appropriately designed plug to pre-stretch the sheet. The plug, which is attached to a movable platen, pre-stretches the hot sheet to an outline similar to, but obviously less than, the internal profile of the female mould (see figure 5).

Figure 10. Plug dimensions and Wall Thickness Distribution with and without Plug.
(From Aroujalian et al. ref. 31)



Schematic of the plug used in thermoforming.



Comparison of wall thickness for strawberry container produced by vacuum and plug-assist vacuum thermoforming.

As further forming takes place after the plug stretching, the plug must not excessively cool the sheet and should not mark the sheet surface. In order to provide sufficient corner thickness whilst maintaining side walls that are thick enough and base not excessively thick at detriment of corner thickness, some slippage may or may not be required. This means that coefficient of friction between hot sheet and plug may be an important factor.

Plug materials can be the same as mould materials or can be a generally available insulating material or a specially formulated material.

Plug materials generally fall into three categories[5].

1) Aluminium. This needs a smooth surface and heating to 5°C less than sheet temperature to prevent chilling and yet avoid sticking.
2) Wood, composite or metal with insulating surfaces. The surface on any material can be fabric or felt, or non-stick plastic.
3) Skeleton plugs made of welded rod, with smooth corners and insulating coating.

In the design of "pre-stretchers", Illig[6] advised keeping a constant spacing between plug and tool all round.

For roll fed (thin sheet) machines, Illig[6] recommended different plug assist materials for different plastics, as shown in the following table:

	POM (Acetyl)	Felt (hardened)	Syntactic Foam
HIPS	-	✓	-
Styrolux	✓	-	✓
PP	✓	-	✓
PP clear	✓	-	-
PVC	-	✓	✓
PVC clear	-	-	✓
PETG, APET	✓	-	✓
PET crystal clear	✓	-	-

1) For PP, felt gives thick cup bottom as too rough.
2) For HIPS, PTFE gives thin bottom.
3) Use PTFE when PE is multilayer outer surface.

6.2.1 Acetal (e.g. Delrin)

1) Cost effective.
2) Problem free fabrication.
3) Best for crystal clear formings.
4) Unsuitable for PVC.
5) Long term exposure to heat limited to 110 – 120°C: surface becomes smoother, discolours and cracks.
6) Surface usually needs roughening every 30 – 100 hours of operation. Exception is polished plugs for crystal clear mouldings.
7) Chilling by cold plug at start-up is no problem with PS.

6.2.2 Hardened Felt

Comments applied to felt hardened with Formulation 647 supplied by Filzfabrik Fulda in sheets up to 80 mm thick.[6]

Alternatively, Clou low viscosity primer can be used to surface harden.

1) Easy start up with PS and PVC.
2) Not used with transparent plastics due to severe marking.
3) Sticks to PP.
4) Easy to install.
5) Relatively expensive.

6.2.3 Syntactic foam

(see item 6 below)

1) Suitable for most materials except for crystal clear mouldings.
2) Dusty machining.
3) Can be cast.

6.2.4 Wood

Solid maple recommended for best sliding properties, but soft textile surface improved sliding and reduced chilling. Plywood is unsuitable as it may leave marks.

6.2.5 Resins

Used for complex shapes. Polyurethane said to be excellent. Plugs can be 100% resin, wood/resin combination or talc filled resin to improve sliding.

6.2.6 "Hytac" Syntactic foams

Matrix Asia Pacific[20] listed 6 materials (including competitors) which had been tested on an in-line thermoforming machine using PP sheet, but few details are given from the conference presentation. Also associated with CMT[34] .

1) "Hytac W" (180°C) and "Hytac R2 (235°C)

Described as a high temperature epoxy based syntactic foam.

- Thermal conductivity as low as 0.08 w/m°K.
- Densities of approximately 0.6 g/cc.
- Improved surface finish (semi-polished from high glass content.

2) "Hytac WF"

Described as a fine surface finish epoxy based syntactic foam.

- "Ultra fine grade" (contains PTFE)
- Improved clarity for APET and other clear polymers.
- Reduces sticking of HDPE and similar polymers.

3) "Hytac B1-X"

Described as a thermoplastic syntactic foam.

- Temperature resistant engineering thermoplastic (unspecified) syntactic foam.
- Improved impact and durability.
- Lower thermal conductivity than Delrin (Acetal).
- Easy to machine.
- 30% higher temperature resistance than Formplast.

These materials were used by Hegemann and Eyerer (IKP Stuttgart) and co-authors Tessier of CMT Materials Inc. and Bush, Fabric-Kal Corpn.(34) Presumably CMT supplied the Hytac materials. A wider range was used as follows:-

Plug Material	Description	Density (g/cc)	Thermal Conductivity (W/mC)
Steel	Used by IKP to determine K-BKZ parameters.	7.8	43
HYTAC-W	Epoxy matrix syntactic foam.	0.63	0.11
HYTAC-B1X	Engineering thermoplastic matrix Syntactic foam	0.74	0.22
Formplast 2000	Solid, thermoplastic polyurethane.	1.2	0.32
Polysulfone	Solid engineering thermoplastic.	1.24	0.26
HYTAC-WT	Epoxy matrix syntactic containing PTFE.	0.74	0.19
HYTAC-B1X, low k-1	Engineering thermoplastic matrix syntactic foam with lower thermal conductivity.	0.67	0.17
HYTAC-B1X,	Engineering thermoplastic matrix	0.67	0.17

Plug Material	Description	Density (g/cc)	Thermal Conductivity (W/mC)
low K-2	syntactic foam with lower thermal conductivity		

4) Formplas 2000

Formplas was described in conference notes by A L Hyde Co.[35] as a thermoplastic rod or slab produced by extrusion. Material composition undisclosed in this text.
(Formplast 2000 was described by Hegemann et al[34] as solid thermoplastic polyurethane).

Technical data was as follows:

- Superior toughness.
- Notched Izod impact strength 10 ft – lb/in.
- Tensile modulus 22,600 Kg/cm^2 ; strong and tough.
- Improved productivity from reduced breakage.
- No surface maintenance required.
- Very low micro-porosity.
- No fillers such as glass or abrasives.
- Machined using standard tools.
- Suitable for thermoforming PS, PETG, HDPE, ABS, PVC, HIPS and PE.
- Particularly good for PP as surface stays smooth over 1000 s of cycles giving blemish free PP surface.

A number of tips for machining Formplast were listed.

6.3 Friction Between Plug and Sheet

As explained above, relative part thickness between wall, corners and bottom for a plug assisted thermoformed container will depend on degree of slippage between plug and sheet. Consequently for both selection of plug material, in particular its surface, and any computer predictions, knowledge of coefficient of friction for the operating sheet and plug surface temperature must be known.

Two research groups have set up experimental rigs while a third has curiously worked backwards by using COF to fit theory to practice [36].

Laroche et al[37] considered the advantage of using thermoplastic forming simulation relied on its ability to predict part thickness distributions as a function of the operating conditions.

Heat transfer and slippage between polymer sheet and plug (two of a number of factors affecting component quality) are difficult to predict or control.

They used plug assisted forming of round cups from PP sheet using Delrin (Acetal ;POM) and syntactic foam plugs. Sheet to plug friction coefficient was measured as a function of temperature and part thickness distributions were compared with predictions.

According to the authors “the surface roughness, the temperature of the interface, the contact pressure and the velocity of the slip also effect the contact friction”.

Coulomb’s Law defines COF (μ) as:

$$\mu = \frac{f}{P}$$

f = frictional force per unit area
P = contact pressure between the two surfaces

For polymers (soft) against metals etc. (hard), friction is more a function of polymer if surface textures are similar. Although there was little published information on influence of temperature and velocity on COF for polymers, thermoforming experiments suggest polymer sheets tend to stick to plugs at thermoforming temperatures.

ASTM D1894 was used to measure COF as a function of pressure and temperature. The test consisted of measuring force to pull a sled over a sheet at a constant speed of 1 m/min (highest on machine, but lower than plug speed) at temperatures ranging from 25 to 160°C.

Thermoforming experiments were carried out producing a 90 mm diameter x 91 mm deep moulding using 1.45 mm PP sheet which was heated in a clamp frame in a convection oven. Vacuum and air pressure with plug assistance was used.
Final thicknesses were measured and compared with predictions by finite element simulation using measured friction data for sheet – plug interface temperatures of 150.7 to 155°C and COF of 0.246 to 0.293.

Agreement between predicted and measured cup thickness distribution were considered good and better than comparisons assuming no slip and no friction.

Hegemann et al[38] measured COF for two polymers against two plug materials:

Polymers	Plug materials
HIPS (amorphous)	Hytac-B1X (syntactic foam)

Polymers	Plug materials
HDPE (semi-crystalline)	Polished steel

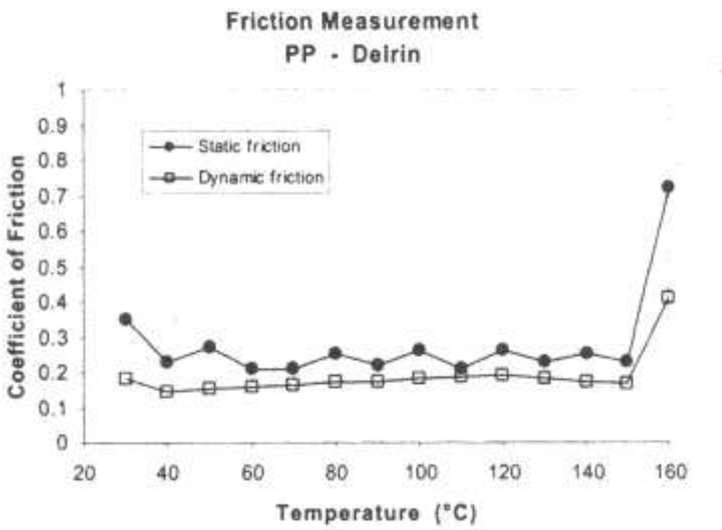
The measurements were carried out using an adapted rotating disc rheometer. This allowed a wide range of speeds, temperatures and normal forces to be used. No significant difference in COF were found over a normal force range of 2 to 20 N. Objectives were to obtain:

1) Consistent results at different temperatures
2) Measurements at thermoforming conditions

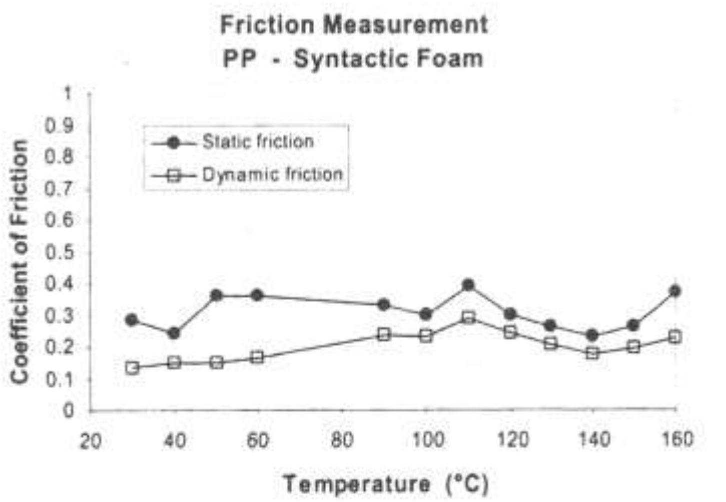
Temperatures were 130 – 170°C for HIPS
130°C for HDPE

Measurements were at 23, 50, 90°C followed by 5 – 10°C steps. Normal force range was 2 to 20 N. A graph was produced of COF v time which showed an initial peak corresponding to coefficient of static friction, followed by an immediate drop to a steady value representing coefficient of sliding friction.

Figure 11. Coefficient of Friction Measurements to ASTM D1894 COF v temperature. (From Laroche et al. ref 37)

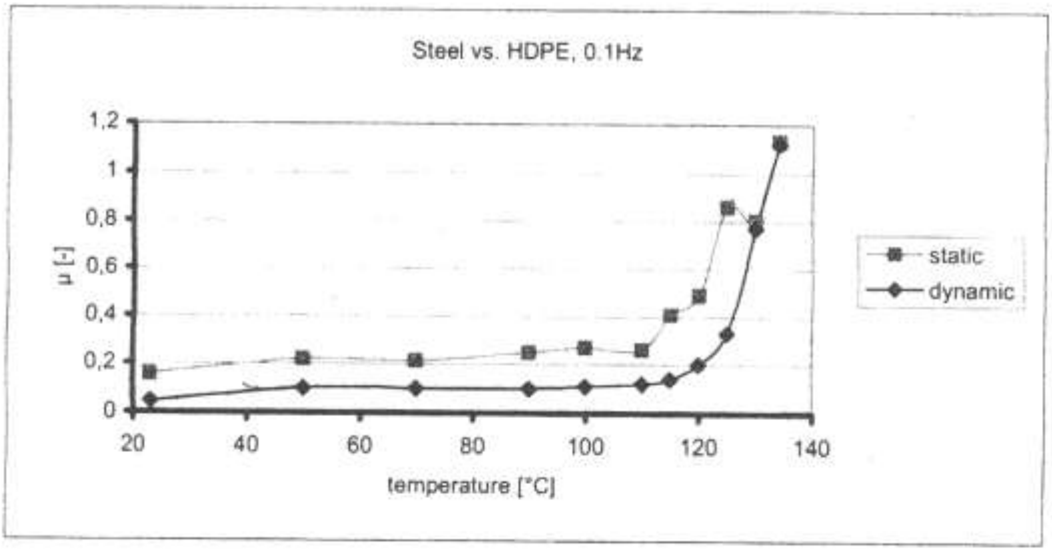


Measured static and dynamic friction coefficients for PP and Delrin as a function of contact temperature.

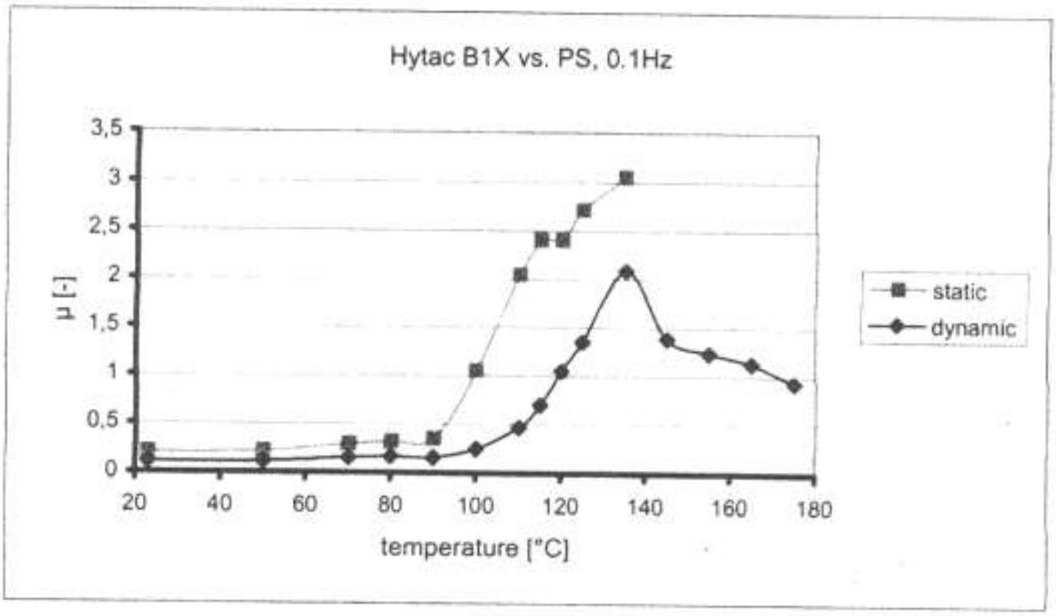


Measured static and dynamic friction coefficients for PP and syntatic foam as a function of contact temperature.

Figure 12. Coefficient of Friction Measurements using adapted rotational viscometer: COF v temperature. From Hegemann et al. ref. 38)



Coefficient of Friction for Steel to HDPE.



Coefficient of Friction for HYTAC® B1X to HIPS

Changes in COF for HDPE against steel with temperature showed a steep rise for both static and dynamic COF at about 115°C. For HIPS against Hytac B1X, static COF rose from about 0.3 to 3.0 over a temperature range from 90 to 130°C, whilst dynamic COF showed a steady rise from about 0.15 to 2.0 over the same range followed by a decline. A T-SIM prediction of force due to friction factors graph was shown. Report figures 11 and 12 show Laroche et al. figure 1 (COF of PP v Delrin) and figure 2 (COF PP v Syntactic foam) (Ref 37) and for Hegemann et al. figure 4 (COF HDPE v steel and figure 5 (COF HIPS v B1X) (Ref. 38).

It should be noted that results in papers by Laroche et al[(37)] and Hegemann et al[(38)] are not directly comparable as Hegemann gives COF v temperature for HIPS against B1X and HDPE against steel but LaRoche's data is for PP against Acetal and syntactic foam.

Tulsion et al[(36)] assessed coefficient of friction using T-SIM simulation software. They varied friction values in the simulation until the thickness distribution predicted was similar to that obtained by experiment.

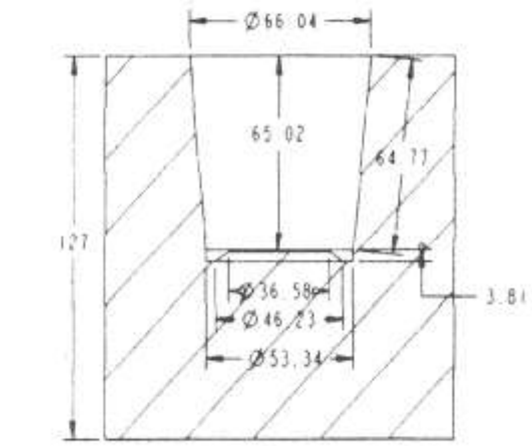
The experimental work used 1.3 mm polypropylene sheet in a vacuum forming machine having an aluminium cup mould. 3 plug materials were used from CMT materials:

Hytac – B1X thermoplastic syntactic foam.
Hytac – B thermoplastic non-syntactic foam.

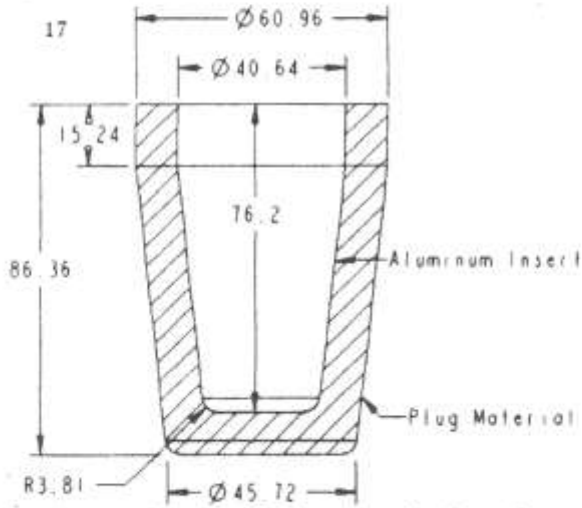
Hytac – WF a high strength/high temperature epoxy syntactic.
The plug core was aluminium with 3 cartridge heaters. Initial mouldings had much thicker walls at the bottom than the sides due to blunt plug shape and deep plug penetrations. As sheet temperature was raised, bottom thickness decreased and corner thickness increased. As plug temperature was increased, bottom thickness increased and corner thickness decreased.

Additional to the increasing plug temperature reducing sheet chilling to allow more stretch into the corners, (making these thinner), the coefficient of friction between plug and sheet may have increased, causing an increase in bottom thickness. Thickness distribution varied depending on the combination of plug material, plug temperature and sheet temperature. Matching of experimental and simulation results to produce COF values, and following good correlation for a sheet temperature of 160°C, it was inferred that average bottom thickness was directly proportional to COF between plug and sheet. Details of cup mould, plug and an example of thickness distribution, are reproduced from Tulsian et al. (30) as Report Figure 13. Tulsian et al. graphs of average wall thickness for wall, corner, and bottom, with changes in sheet temperature and similarly for changes in plug temperature are shown in Report Figures 14 and 15 respectively (see next pages).

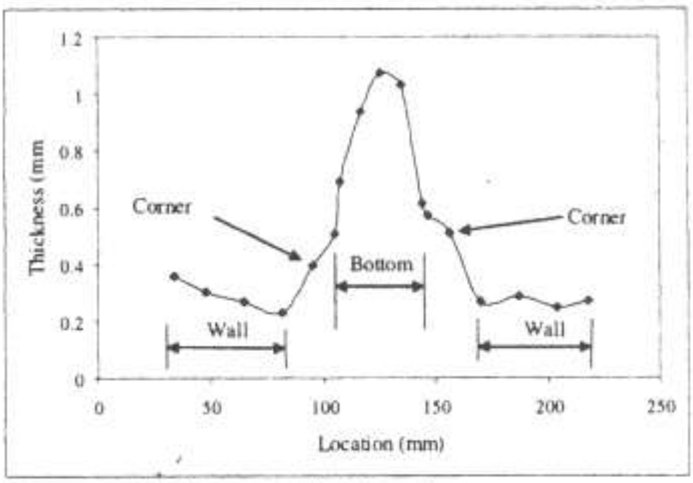
Figure 13. Mould and Plug Dimensions and Thickness Distribution.
(From Tulsian et.al. ref. 36)



Dimensions of cup mold.



Dimensions of plug and aluminum insert.



Thickness distribution.

Figure 14. Effect on Wall Thickness Average for Wall, Corner, and Bottom by Changes in Sheet Temperature. Plug temp. 30 °C. (From Tulsian et al. ref. 36)

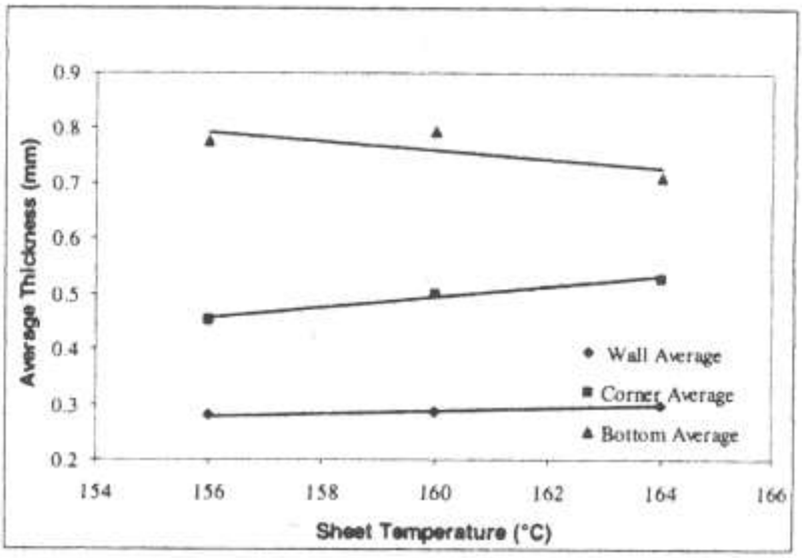
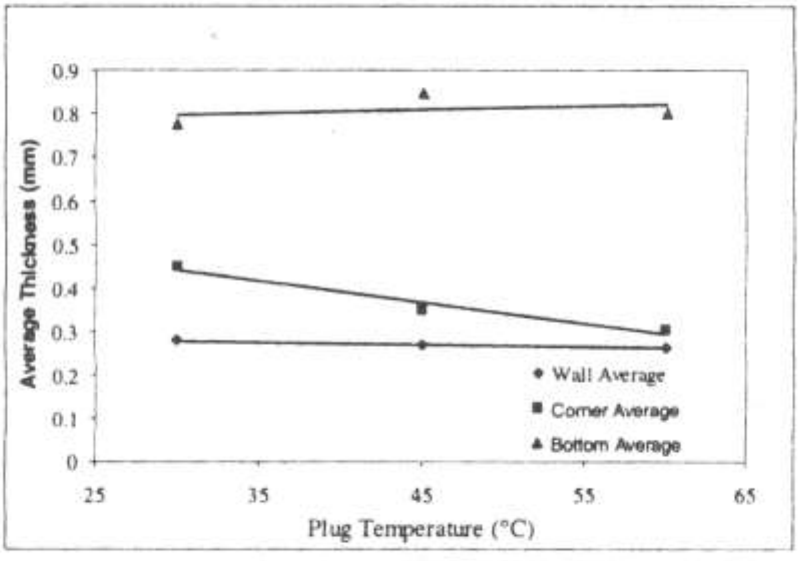


Figure 15. Effect on Wall Thickness Average for Wall, Corner, and Bottom by Changes in Plug Temperature. Sheet temp. 156 °C (From Tulsion et al. ref. 36)



6.4 Mould Plug and Heat Transfer

Collins et al[39] investigated heat transfer at the plug and mould interfaces in order to improve wall thickness prediction. Most finite element models were said to assume isothermal conditions, but in this case, wall thickness predictions were compared for a thermoformed container between isothermal and non-isothermal conditions.

From measurements on an industrial machine, sheet temperature was 150°C, plug temperature 100°C, and mould 10°C with sheet 1 mm thick. Heat transfer was therefore greatest from sheet to mould. The model showed that the amount of heat transfer removed from the sheet by the plug was dependant on the thickness of the sheet in contact with the plug. With mould contact, the sheet lost heat very quickly and contact time was longer, so heat was lost to the mould and by convection.

Collins et.al.[42] investigated the combined effects of coefficient of friction and heat transfer between sheet and plug after adding data reported in (37) and (39) described above. Aluminium was added to Acetal and Syntactic foam to provide a range of plug thermal conductivities, measurements of wall thicknesses and weighings of material contacting the plug tip using plug only.

It was shown that during the brief contact between plug and sheet, heat loss was sufficient to influence forming, being greatest for aluminium and least with Syntactic foam. Weighings of sheet cut from the plug tip showed increasing plug temperatures, reduced sheet cooling and with low friction, the sheet was lighter (i.e. thinner) at the tip. Above 100 ^{0}C the COF began to predominate with the sheet surface beginning to stick and the bottom becoming heavier (i.e. thicker).

Kamal et.al.[40] were quoted, that inner surface cooling speeded up production rate, confirmed by Birley et al[41] but considered the amount of cooling was slight compared with conduction to the model wall. Experimental work for verification and friction measurements were needed.

6.5 Plug Assisted Forming Experimental Work

There is very little practical data on plug assistance. In a paper by Tulsion et.al.[36]. measurements were carried out to verify computer predictions including COF as summarised in section 5.3.

Hegemann et ai [34] described experiments using a range of plug materials for force measurements using HDPE sheet.

1) Steel used for K-BKZ parameters
2) HYTAC-W . Epoxy Matrix syntactic foam
3) HYTAX-81X
4) Formplast 2000
5) Polysulphone
6) HYTAC-WT
7) HYTAC-BIX. Low k –1
8) HYTAC BIX Low k-2

(For more details see table in section 5.2.6).

Two plug shapes used were; a truncated cone with a sharp radius on the leading edge where the plug first contacted the sheet. This proved unsuitable with the HDPE as it tore the sheet. The second plug had a hemispherical rounded end. Tests were carried out using a high speed servo-hydraulic testing machine fitted with an oven. Following assembly, clamp plug and sample were heated in the oven. The test consisted of impacting the sample with the plug at a set velocity to deform the sheet to a depth of 40 mm. Force was measured by a force-cell at the plug tip and displacement by piston travel.

The HDPE sheet had Tm about 134°C and Tp about 132°C. Chosen sheet temperatures were 118, 125 and 132°C. Plug temperatures were 80°C or same as oven temperature. Deformation velocities were; 2.0, 200, and 500 mm/s. (Note: all results were for the round plug). For Hytac-W epoxy syntactic, increasing sheet temperature and plug, decreased peak force but there were greater increases with increasing plug speed.

Comparing a rough surface plug with one having a smooth surface; at the higher temperatures the rough surface plug reduced force by 25% and there was a 14% reduction for the polished plug. Increases in peak force due to plug speed were 56% for the rough surface and 45% for the smooth surface.

With Formplast 2000 there was a significant increase in peak force; the 80°C plug temperature compared with the plug at the sheet temperatures, by an average of 82%. The effect of plug speed was the same as before with the plug temperatures superimposed.

Measurement of formed sheet tip thickness showed no significant difference except at 118°C sheet temperature when it increased 12% and 20% at 20 and 500 mm/s plug speed respectively.

With the Formplast 2000 plug (rough surface) peak force increased with sheet thickness but not in proportion.

Probably the most interesting results with regard to this review were those comparing peak force and tip thickness for different plug materials. The rounded plug shape with rough surface was used. Their observations can be summarised as follows:

1) Hytac. W epoxy syntactic. Highest peak force. Lower tip thickness.
2) Hytac-B1X. ETP syntactic. 2nd lowest increase in peak force due to plug speed. Highest decrease in tip thickness.
3) Hytac-WT. epoxy syntactic with PTFE. Lowest peak force. Thickest tip regardless of plug speed.
4) Formplast 2000. Highest increase in peak force due to plug speed. Lowest decrease in tip thickness?
5) Polysulphone. Lowest decrease in force due to increased temperature at 20 mm/s. Least % increase in peak force due to increased speed at 132^{0}C.

In order to get stress / strain data at elevated temperature under plug stretching conditions, Martin et al. (55) modified an instrumented falling weight impact testing machine such that the forces involved in pushing the plug to its normal forming depth could be measured. The machine's striker was replaced with a miniature hemispherical plug made from syntactic foam for PS testing and Delrin (polyacetal) for PP as in industrial practice. Overall weights were 7 and 9 Kg to produce 0.8 and 1.2 ms^{-1} impact velocities. With a built-in oven, test temperatures were between 120 and 155 ^{0}C for PS and 150-160 ^{0}C for PP. Height was set at lowest setting and to simulate different mould clearances, samples were clamped against different diameter washers.

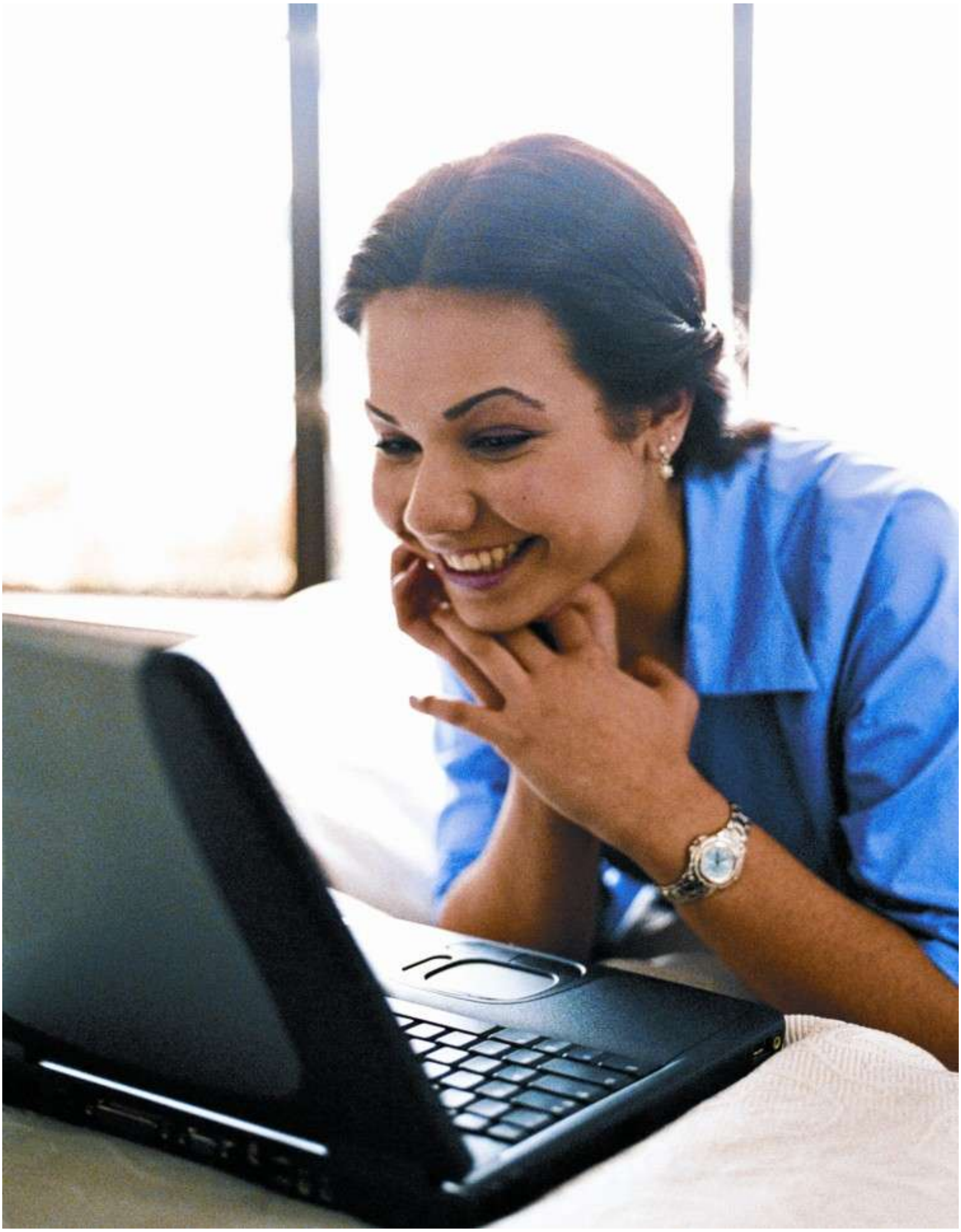
As sheet temperature increased, the sheet modulus dropped, but whereas that for PS was virtually constant above 130 ^{0}C after falling from 120 ^{0}C, the PP at a higher modulus fell rapidly over the 140-160 ^{0}C range, reflecting its narrow processing window.

However, although the results were useful in the short term, it was decided to design and build a fully instrumented biaxial stretching machine.

T-ForM

SIXTH FRAMEWORK PROGRAMME

ProducentenVereniging Thermoplasten



T-ForM

SIXTH FRAMEWORK PROGRAMME

ProducentenVereniging Thermoplasten

7. Computerised process simulation

7.1 Background

To quote Stephenson and Ryan[43]:

"As thermoforming vigorously pursues markets such as the auto-industries, the growth of computer-aided engineering will incorporate mathematical modelling of the process to enhance the design and optimisation of the process and ensure tight accuracy and reliable repeatability/production of the part."

"Development of a reliable model requires extensive material characterisation and experimental thermoforming studies conducted under controlled conditions which simulate commercial operations. The literature contains relatively little data with regard to material characterisation and experimental thermoforming operations."

Throne[7] listed 14 reasons for computerising the entire thermoprocessing process which can be summarised as follows:-

1. Extrusion of pellets into sheet is an added cost.
2. Normally 25 – 50% of this sheet becomes scrap to be reprocessed.
3. Process is energy intensive.
4. Average final part thickness is far less than initial part thickness.
5. Parts have non-uniform thickness, often very thin at corners.
6. Part performance depends on stretching, thinnest loaded sections and corner designs.
7. Wasteful of material in areas thicker than necessary.
8. CAE of the process covers all sequences from sheet temperature to cooling.
9. CAD is only one facet of CAE.
10. Assumption of large scale isothermal biaxial stretching of an isotropic elastic sheet is easiest approach.
11. It also allows 2D FEA to be used for wall thickness.
12. Initial volume minus that already contacting mould wall is volume still free to stretch.
13. CAE may be of greatest value for sheet giving barrier properties.

Knights in an editorial review in 1998[44] stated that demand for blow moulding and thermoforming process simulation had been very slow up to that date, but the situation was changing. However the interest was far more for blow moulding then thermoforming.

Contributors considered that thermoformers (and blow moulders) relied on educated guesswork and trial and error but that simulation gave guidelines for tool design and process simulation. Many advantages were claimed for blow moulding. A respondent on thermoforming warned that simulation did not give absolute answers but was just a tool, which identified trends and did not fit every product. Applications were appropriate for tight tolerance products such as automotive and also for new materials.

The process was as follows:

1) Starting point was a CAD model either imported or drawn from scratch.
2) Generate a finite element mesh on the model.
3) Model of material behaviour.

Effects of plug assist can be modelled. Packages might provide “freeze-frame” images or animation, and some could by then take plastic flow into account in addition to elastic stretching; useful for longer cycles with large parts. Sheet sag, elastic yield and strain hardening could be taken into account. On completion of simulation, the results can be exported to an FEA structural-analysis programme to estimate shrinkage.

3-D was the preferred system but two companies were named as supplying 2D options for speed but with less detail. Systems mentioned for thermoforming were Compuplast’s T-SIM which ran on a Windows PC, C-Mold based on GE’s 1994 prototype with 3D and 2D simulation, and Polydynamics T-Formcad which had only sheet stretching and no cooling or viscoelastic model.

Sherwood were introducing TF202 for heating rates and temperatures, T505 for local sheet temperatures, and T213 for oven heating profiles and subsequent mould cooling. IMI-CNRC was developing a thermoforming package for 1999.

Number of users, where disclosed, was 10 for Compuplast T-SIM, C-mold was 93 including blow moulders, Polydynamics T-Form had 4 licensees and 20 – 30 users. IMI-CNRC (Industrial Materials Institute of the Canadian National Research Council) assembled a consortium of 11 thermoforming companies to develop new simulation software. The University of Massachusetts was intending to offer a suite of simulation software tools for its web site, with the aim of predicting part tolerance to within 0.2% of normal dimensions.

In an April 2005 review[45], Aicaform’s T-SIM (from Compuplast International) simulates positive/negative forming with or without plug assist, predicting final wall thickness distribution. Process variables included pressure, tool speed and sheet temperature distribution.

Kouba et al(46) briefly reviewed progress on modelling of thermoforming up to that point in 1994, with 8 references, and considered that virtually all simulations neglected viscoelastic effects. The final thickness distributions were, as shown by industrial experience, to be largely dependant on strain hardening characteristics. Consequently, visco-elastic effects should be taken into consideration.

The stated list of features of the current model described can be summarised as follows:-

1) No limit on sheet shape.
2) Constant or variable sheet thickness.
3) Constant or variable sheet temperature distribution.
4) Complex mould cavities can be easily created.
5) The sheet can be refined as necessary regarding contact areas etc.
6) Sheet stretching with or without plug assist.

Tshai et al(47) considered the available material models were often incapable of accurately describing the variables in the forming process particularly for polypropylene. The K-BKZ (Bernstein, Kaersley, Zapas; ref v) was used for PP in T-Sim and Polyflow software but was considered to be less accurate in terms of yielding and strain hardening for PP.

The difficulties of achieving accurate predictions of part thickness by using computer predictions/finite element analysis can be appreciated from the only comprehensive empirical paper found. This work by Ayham and Zhang(2) applied to a production form-fill-seal (and sterilisation) machine, but being a thin sheet process, the results will be confined to this sector of the thermoforming industry. The programme was essentially the influence of production conditions on the wall thicknesses of the part at a range of wall positions and cavity locations.

Thermoforming used a plastic plug assist into a female mould with compressed air for final forming into the chilled mould at 21°C. The material was a co-extruded sheet of HIPS/adhesive/Saran/adhesive/LDPE. It was stated that getting uniform container thickness was particularly important to provide required barrier properties. Sheet thickness was 1.45 mm. Tooling consisted of “a pair of stainless steel female moulds with aluminium bottom inserts and a pair of stainless steel upper moulds with plastic plugs for clamping and pressurising”. Details of plastic used for the plugs were not included.

Measurements of wall thickness at locations of 0, 10, 20, 30, 40 and 50 mm from rim of cup (total depth 52 mm) showed higher temperatures decreased thickness at rim and increased thickness towards bottom. Temperature range was from 131 to 170°C with most significant changes being in the 146 to 165°C range.

With higher forming temperatures, stretching continued for a longer time, resulting in decreased thickness near the rim; confirming findings of Potter and Michaeli (SPE Antec 1992 p104). There were also variations with location and sides of container depending on relative heating contributions between sides and central heaters. The hotter part stretched more near the rim. Above 165 and 170°C, walls were very thin and delamination occurred. Increasing the forming pressure over a range from 2 to 4 bar showed similar effects to increasing temperature but to a lesser degree.

Vacuum forming experiments were carried out by Stephenson and Ryan(43) using an aluminium female mould diameter 101.6 mm having an adjustable bottom depth. Depth used was 46.8 mm. Pressure changes during the process were measured with a sensitive pressure transducer and contact times at points in the mould surfaces were measured from wall contact sensors. 0.76 mm and 1.17 mm transparent styrenic sheet was used, printed with a grid pattern of radial lines every 15° and concentric circles spaced 6.35 mm. Measurements were made under process conditions of 130, 140 and 150°C sheet temperatures and high, medium, and low evacuation rates. Results were tabulated for variation of 1) total pressure differential, 2) extension ratio data and 3) final part thickness. Final part tensile property data was also tabulated.

It was observed that the sheet was first stretched into an approximate spherical shape, contacted the mould centre-bottom, then the sides and it finally stretched into the corners. The stretch ratio, which was slightly larger for the 0.76 mm sheets was always larger in the machine direction than the transverse direction. The corners were thinnest, having experienced the greatest stretch.

Tensile strength and elastic modulus of samples from the bottom were slightly higher and elongation at break was significantly higher compared with original sheet.

7.2 Forming feometries

The material volume will be the same after drawing as it was at the start (Throne(7)).

$$\text{i.e.} \qquad V = t_o A_o = t_a A_a$$

where V = volume, t_o = original thickness, A_o = original area, t_a = average wall thickness of final thermoforming, A_a = area of final thermoforming.

Although vacuum forming produces parts with non-uniform wall thickness, average part thickness is used for Areal Draw Ratio, the simplest expression for stretch.

$$R_a = A/A_o = t_o/t_a$$

Throne also cites other expressions for “Areal Draw” ratio: “stretch ratio”, “stretching ratio”, “stretch factor”, and “areal elongation”. He also tabulates areal draw ratio for 9 different shapes, and refers to a paper which recommended that calculated area draw ratio values be increased by 50% of the sheet surface used between lip and clamping ring to allow for material drawn from the lip region into the cavity. Throne also illustrates the use of average draw ratios for selection of a polymer with suitable draw properties, and uses the “conical female mould” to illustrate the relationship between draw ratio and local sheet thickness. Thickness equations for other shapes, pre-stretching and material properties are then given.

The tabulated complex analytical schemes were said to be best solved with computers. Finite element analysis was a more practical way of calculating wall thickness. The method of applying FEM was described.

7.3 Computer simulation literature summary

(Very brief summaries based on Rapra abstracts).

Although several computer simulation articles have been reviewed for their practical experimentation directly relevant to tooling, a comparatively large number of computer simulation papers have been published, particularly at SPE ANTEC conferences. For completeness, the companion papers by the same organisations are reviewed very briefly below together with other papers in this field. Reviews within each grouping are arranged in publication date order from this abstract search start date of January 1996.

The Canadian National Research Council (with collaborators) has produced at least 5 papers as follows:

- Derdouri A et al[(48)] showed with ABS sheets at 145°C that bubble inflation tests using pressure versus height at the hemispherical pole were useful in determining material constants for thermoforming simulation. (See also 70 and 71).

- DiRaddo et al[(49)] modelled the vacuum forming process using a non-isothermal viscoelastic constitutive equation. Good agreement was obtained between model predictions and experimental measurements of a box formed using ABS.

- DiRaddo and Aubert(50) predicted phase change dynamics, in particular quiescent crystallinity development and thermal history for both PP and heat set PETP for blow moulding and thermoforming. Crystallinity predictions were compared with industrial scale blow moulding results.

- Laroche D et al.(51) simulated thermoforming a boat hull from HDPE using FEA and the results compared with actual measurements. Although there were 20°C discrepancies between predicted and measured temperatures as well as sheet sag being nearly twice actual value, there was good agreement between predicted and measured values of final thickness.

- Debegue et al(52) evaluated a series of numerical models for sag prediction by comparing with experimental results. Chyan Yang et al(53) modelled and optimised thermoforming of PET using an inverse back propagation neural network model. This took into account network inputs, which included thickness distribution at different positions of the moulded parts. Computed results were compared with experimental data.

In addition to those covered in previous sections, there are at least three further papers from Queens University Belfast and a joint paper (37 above) with Can. Nat. Des. Council. Lappin et al(54) described an FEA model involving both 2D axisymmetric and 3D geometry with simulation of material behaviour using a viscoelastic model based on material test data. It was concluded that inclusion of viscoelastic effects was important for predicting wall thickness distribution.

- Martin et al(55) obtained stress-strain data for polystyrene and polypropylene under high strain rates using a falling weight impact tester fitted with a hemispherical indenter to simulate plug-assisted thermoforming conditions. The stress-strain data was derived from force-displacement curves using sheet samples heated to thermoforming temperatures.

- Tshai et al(47) proposed a modelling approach for thin gauge solid-phase thermoforming of polypropylene which precisely described the yield strain softening followed by flow and hardening as observed in hot-drawing. The K-BKZ model was said to be exclusively used to describe PP behaviour in T-SIM and Polyflow simulation software. Bioaxial stretching of polypropylene samples at 140°C and strain rates of 2 sec^{-1} were described. The results were used in the development of a 2D model with the potential to be used in thermoforming simulation.

- IKV (Aachen) have been involved with two papers but a lot of their relevant work is in the form of dissertations etc. which are listed in their references.

- Michaeli and Hartwig[56] showed that biaxial stress/strain data for use in simulation of thermoforming (as well as blow moulding) can be obtained using a bubble inflation rheometer.

- In a pre-computing developments progress report on process simulation, Michaeli W et al[57] discussed simulation programme principles and uses in industry of simulation software to design processes, dies and moulds including thermoforming.

Massachusetts University who have used T-SIM in the two papers found.

- Haihong Xu and Kazmer D O[58] developed an analytical method for shrinkage predictions based on a viscoelastic constitutive material model with initial conditions from a commercial thermoforming simulation. The results indicated that the estimated shrinkages from the analysis were within 0.1% of predicted part dimension error.

- Tulsian A et al. [36] assessed COF by varying values in T-SIM simulation software until the thickness distribution predicted by simulation was similar to that obtained experimentally. COF between plug and sheet was determined by this method for epoxy syntactic, engineering thermoplastic non-syntactic and syntactic and PP sheet.

The first T-SIM references found were in 1996/7 with a review in 1998.

- This article[59] described the background and features of T-SIM which included visualisation of the shape and thickness distribution of the sheet at all stages of the inflation process, a 3D picture observing all part section in x, y or z plane, colour spectrum material thickness indication, zoom functions and local temperature information, C Meier has also reviewed this software[60], although the most detailed description is that of Doll and Kouba[61].

A number of other papers were found as follows:

- Thrasher M A[62] used FEA to predict heating rates and temperature profiles throughout sheet cross section, explaining the finite element modelling and aspects of heating polymer sheet.

- Debbaut and Homerin[63] gave details of their numerical solution of the thermoforming process which included prediction of sheet motion, thickness and extension distributions.

- In the article by Rachik and Roelandt[64] headed – "unified approach for thermoforming numerical simulation" – a numerical solution was used to solve the global equilibrium equations and to integrate the sheet viscoelastic constitutive model.

- Nam et al[65] compared results of laboratory-scale thermoforming experiments for ABS with predictions of a hyperelastic material model. Material parameters of this model were obtained from unidirectional hot tensile tests and two simulation techniques were compared.

- Wang and Nield[66] developed a model where the initial temperature distribution to obtain a specified final thickness distribution is determined. The results for a deeply drawn thermoformed ABS part were sensitive to changes in the initial temperature profile, suggesting that high precision thermal sensors and controls may be required in practice.

- R Christopherson et al[67] used non-isothermal FEA in conjunction with simulation software to model the formation of pharmaceutical blister packs by plug-assisted thermoforming. The model was validated using coated PVC, the current material before being used for a cyclic olefin copolymer coated on both sides with PP, where the results were considered just acceptable.

- Pantelelis N G et al[68] have simulated vacuum forming a large complex refrigerator panel using FEA and various numerical tools, and the results compared with production data. It was proposed that simulations were an alternative to expensive and time consuming trial and error procedures.

- J L Throne[69] tabulated computer simulations for blow and rotational moulding in addition to thermoforming and included constitutive equations and process simulation.

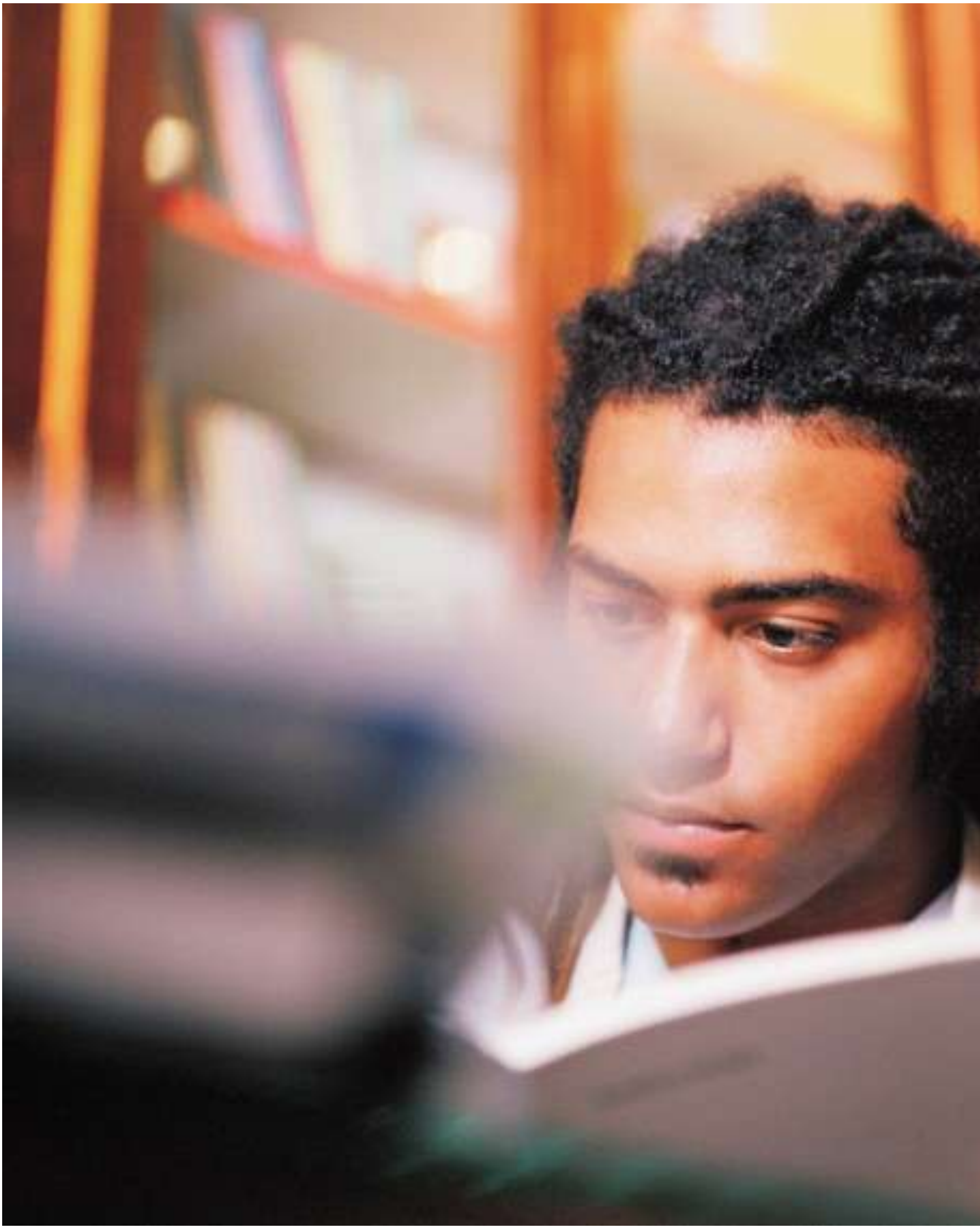
- Dong et al[70] used results of uniaxial tensile tests at 150 – 190°C in PMMA sheet to derive parametric functions in terms of forming temperature which were applied in free inflation bubble profile simulation. Results showed promising agreement with experimental data.

- Several authors refer to Kamal and Kalyon[40] who made experimental measurements of heat transfer in cooling blow mouldings and got good agreement with results from a finite difference computer simulation. There are also references to Lai and Holt[71] who measured wall thickness of free formed axisymmetric domes in PMMA and HIPS and found that at given height the PMMA was thicker than the HIPS (see also [70]). It was concluded that a large negative value of the "stress relaxation index" reduced uniformity of sheet thickness.

T-ForM

SIXTH FRAMEWORK PROGRAMME

ProducentenVereniging Thermoplasten



T-ForM

SIXTH FRAMEWORK PROGRAMME

ProducentenVereniging Thermoplasten

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Appendix

Planoxal-50 Aluminium Data Sheet

algroup **alusuisse**
fabricated products

alusuisse nederland bv t +31 76 542 52 00
aluminiumstraat 1, 4823 al breda f +31 76 541 88 99

Technical Data Sheet

PLANOXAL®-50

EN AW-5083 / AlMg 4.5 Mn

January 2000 edition

BRIEF DESCRIPTION

Planoxal®-50 plates differ from other standard EN-AW 5083 alloy products in that it has a low level of internal stress. It is also suitable for technical anodisation.
Planoxal®-50 is mainly used for low stressed machine elements, which are subject to heavy machining, particularly for parts that require anodisation against corrosion and contamination.
Applications include packaging, printing and food conditionning machines.

PROCESSING METHODS

Weldability
- TIG/MIG — excellent
  Filler material — AA5183, AA5386
- by resistance — excellent

Anodisation
- technical — excellent
- decorative — excellent

Machinability — good

Corrosion behaviour
- excellent in inland atmosphere
- good in marine atmosphere

AVAILABILITY

Planoxal®-50 is available in H111-temper (annealed – stretched) in the following sizes :

Thickness	**Dimensions**
8 – 20 mm	1520 x 2520 mm
21 – 50 mm	1520 x 3020 mm

(other dimensions on request)

Flatness	**Max.**
over width	2 mm/m
over length	1 mm/m

PROPERTIES

Chemical composition (weigth %)

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti +Zr
max. 0.4	max. 0.4	max. 0.10	0.40 1.00	4.0 4.9	0.05 0.25	max. 0.25	max 0.15

Physical properties (typical values)

Density	2.66 g/cm^3
Elastic modulus	71000 MPa
Linear thermal expansion coeff. (20°-100°C)	23.8 10^{-6} K^{-1}
Thermal conductivity	105 - 120 W / m K
Electrical conductivity (20°C)	15 - 17 m/Ωmm^2

MECHANICAL STRENGTH

Minimum garanteed values (Standard EN 485-2 / Temper 0/H111)

Thickness (over ... to)	Rp0.2 [MPa]	Rm [MPa]	A50 [%]
8.0 - 12.5 mm	125	275	16
12.5 - 50 mm	125	275	15

Typical mechanical properties for various gauges

Thickness (over ... to)	Rp0.2 [MPa]	Rm [MPa]	A50 [%]	Hardness* HB
8.0 - 20 mm	150	295	23	77
20 - 50 mm	140	295	23	76

* For information only

Prolonged exposure to temperatures exceeding 70°C can provoke susceptibility to intercrystalline corrosion.

Planoxal-60 Aluminium Data Sheet

algroup alusuisse
fabricated products

alusuisse nederland bv t +31 76 542 52 00
aluminiumstraat 1, 4823 al breda f +31 76 541 88 99

Technical Data Sheet

PLANOXAL®-60

EN AW-6082 / AlMgSi 1

January 2000 edition

BRIEF DESCRIPTION

Planoxal®-60 plates differ from other standard EN-AW 6082 alloy products in that it has a low level of internal stress. It is also suitable for technical anodisation. Planoxal®-60 is mainly used for medium stressed machine elements, which are subject to heavy machining, particularly for parts that require anodisation against corrosion and contamination. Applications include packaging, printing and handling machines.

PROCESSING METHODS

Weldability
- TIG/MIG — excellent
  - Filler material : AA5356, AA4043
- by resistance — excellent

Anodisation
- technical — excellent
- decorative — excellent

Machinability — good

Corrosion behaviour
- excellent in inland atmosphere
- good in marine atmosphere

AVAILABILITY

Planoxal®-60 is available in T651-temper (quenched - stretched - artificially aged) in following sizes :

Thickness	Dimensions
8 - 20 mm	1520 mm x 2520 mm

(other dimensions on request)

Flatness	Max.
over width	2 mm/m
over length	1 mm/m

PROPERTIES

Chemical composition (weight %)

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti +Zr
0.70 1.30	max. 0.50	max. 0.10	0.40 1.00	0.60 1.20	max. 0.25	max. 0.20	max 0.15

Physical properties (typical values)

Density	2.70 g/cm³
Elastic modulus	69000 MPa
Linear thermal expansion coeff. (20°-100°C)	23.4 10^{-6} K^{-1}
Thermal conductivity (temper T651)	150 - 170 W / m K
Electrical conductivity (temper T651, 20°C)	24 - 28 m/Ωmm²

MECHANICAL STRENGTH

Minimum guaranteed values (Standard EN 485-2 / Temper T651)

Thickness (over ... to)	Rp0.2 [MPa]	Rm [MPa]	A50 [%]
8 - 12.5 mm	255	310	9
12.5 - 20 mm	240	295	8

Typical mechanical properties for various gauges

Thickness (over ... to)	Rp0.2 [MPa]	Rm [MPa]	A50 [%]	Hardness* HB
8 - 20 mm	305	350	11	105

*For information only

Heating the alloy can result in loss of strength of properties or of capability for fabrication, assembly or application in a particular case.
The information in this publication does not imply a guarantee of properties or of capability for fabrication, assembly or application in a particular case.

T-ForM

SIXTH FRAMEWORK PROGRAMME

ProducentenVereniging Thermoplasten

RenShape® BM 5055

RenShape® solutions

Board Material

RenShape® BM 5055

Epoxy board for pre-preg tools

Key properties

- **Very fine surface structure**
- **Excellent machinability**
- **Good dimensional stability**
- **Heat resistant up to 140°C**

Applications

- Lay up tools for pre-pregs
- Data control and cubing models
- Vacuum forming moulds

Product data

Product	Colour	Test method
RenShape BM 5055	Light green	visual

Properties

Density	ISO 1183	g/cm³	0.72 - 0.75
Hardness	ISO 868	Shore D	75
Coefficient of thermal expansion	ISO 11359	$10^{-6}K^{-1}$	35 - 45
Deflection temperature	ISO 75	°C	135 - 140
Compressive strength	ISO 604	MPa	50 - 55
Compressive modulus	ISO 604	MPa	2300 - 2400
Flexural strength	ISO 178	MPa	30 - 40

Bonding

System		RenGel® SW 18 Ren® HY 2404	RenGel SW 18 Ren HY 5159
Appearance	visual	Green	Green
Mix ratio	Parts by weight	100 : 20	100 : 16
Pot life at 25°C (0.5kg app.)	min	10 - 15	25
Clamping time	h	1	3
Cure schedule	4h at 80°C plus 4h at 120°C plus 4h at 140°C		

Note: Prepare the surfaces to be bonded with abrasive paper then clean to ensure the surfaces are oil and dust free. Apply the adhesive evenly to all surfaces that are to be bonded.
Ramp up at no more than 10°C per hour and hold for the recommended time. Ramp down by no more than 10°C per hour following the cure schedule in reverse until the oven has reached 40°C, then switch off and do not open the oven for 10-12 hours until the tool has reached ambient.

Repair

System		XD 4586 A/B
Appearance	visual	Green
Mix ratio	Parts by weight	100 : 19
Pot life at 25°C (0.1 kg)	min	20 - 30
Cure time at RT 20 mm layer thickness 1-2mm layer thickness		 approx. 1 hour over night

Note: Recommended Release Agent: ACMOSAN 82-7007 (ACMOS CHEMIE)
Recommended surface paint: EC85 Epoxy surface paint (Amber Composites) or Cyform Hard Paint (Cytec Fiberite). These materials can be obtained from the producers directly or through Vantico distributors.

Milling

Milling parameter available on request.

Storage

Board material may be stored flat in original cartons at 2° to 40° C in a dry area. Temperature variations should be avoided when transporting and storing board material.

Working condition

The product should be used when in the temperature range 20° to 25° C.

Packaging

Dimensions	Volume (l)	Weight (kg)	Number of Boards (per pack)	Number of Boards (per pallet)
1500 x 500 x 50	37.5	28	2	5
1500 x 500 x 100	75	56	1	5

Handling precautions

Caution

Our products are generally quite harmless to handle provided that certain precautions normally taken when handling chemicals are observed. The uncured materials must not, for instance, be allowed to come into contact with foodstuffs or food utensils, and measures should be taken to prevent the uncured materials from coming in contact with the skin, since people with particularly sensitive skin may be affected. The wearing of impervious rubber or plastic gloves will normally be necessary; likewise the use of eye protection. The skin should be thoroughly cleansed at the end of each working period by washing with soap and warm water. The use of solvents is to be avoided. Disposable paper - not cloth towels - should be used to dry the skin. Adequate ventilation of the working area is recommended. These precautions are described in greater detail in the Material Safety Data sheets for the individual products and should be referred to for fuller information.

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EPO 4042 / EPO 4042/L

AXSON

EPO 4042 / EPO 4042/L

EPOXY CASTING RESIN FOR VACUUM FORMING

Tg 80°C – LOW VISCOSITY

DESCRIPTION

Production vacuum forming moulds and tools for injecting polyurethane foams.

PROPERTIES

- *Low viscosity*
- *Very good surface finish after machining*
- *Aluminium filled to give good thermal conductivity*
- *Two reactivity available*
- *Casting until 70 mm thickness*

PHYSICAL PROPERTIES				
Composition		RESIN EPO 4042	HARDENER EPO 4042	HARDENER EPO 4042/L
Mix ratio by weight		100	7	7
Aspect		thick liquid	liquid	liquid
Colour		aluminium grey	red	blue
Viscosity at 25°C(mPa.s)	BROOKFIELD LVT	70,000	260	80
Density at 25°C	ISO 1675 : 1985	1.73	0.98	0.94

Viscosity at 25°C	BROOKFIELD LVT	mPa.s	16,000	17,000
Specific gravity at 25°C	ISO 2781 : 1996		1.71	1.71
Pot life at 25°C on 250g	-	min.	135	220

MECHANICAL AND THERMAL PROPERTIES at 23°C (1)				
			EPO 4042	EPO 4042/L
Hardness	ISO 868 : 2003	Shore D15	88	89
Flexural modulus	ISO 178 : 2001	MPa	6,200	6,000
Flexural strength	ISO 178 : 2001	MPa	57	52
Flexural strain at flexural strength	ISO 178 : 2001	%	1.3	-
Compressive strength	ISO 604 : 2002	MPa	104	103

(1) : Average values obtained on standard specimens of pure resin / Hardening 24 hr at room temperature + 2hr at 60°C + 2hr at 80°C.

PROCESSING CONDITIONS – EPO 4042

Thoroughly mix the resin before use and ensure a homogeneous mix according to the indicated ratio and then cast. After hardening for 24 to 36 hours at room temperature it is recommended to post cure 2 hours at 60°C and 2 hours at 80°C . For casting above 50 mm we would advise alternative aluminium granular fillers or use EPO 4042/L hardener for until 70 mm thickness.
For further information, consult our technical department.

PROCESSING CONDITIONS – EPO 4042/L

Process as above. Product can be demoulded 24 hours but remains delicate in thin section. In this case we recommend product rests for a further 24 hours before demould.
POST CURE (24 hour demould) 2 hrs at 40°C, then 2 hrs at 60°C, then 2 hrs at 80°C
POST CURE (48 hour demould) 2 hrs at 60°C, then 2 hrs at 80°C

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AXSON

EPO 4042 / EPO 4042/L

EPOXY CASTING RESIN FOR VACUUM FORMING
Tg 80°C – LOW VISCOSITY

THERMAL AND SPECIFIC PROPERTIES AT 23 °C

			EPO 4042	EPO 4042/L
Temperature of glass transition • After 3 days at 23°C • After 2 hrs at 60°C • After 2 hrs at 60°C + 2 hrs at 80°C • After 16 hrs at 80°C	ISO 11359 : 2002	°C	44 53 79 -	42 48 74 80
Coefficient of thermal expansion (CTE) (+5° to +50°C)	ISO 11359 : 1999	10^{-6} K^{-1}	50	43
Linear shrinkage (specimen 250x50x3mm)	-	mm/m	1.30	0.5
Maximal casting thickness	-	mm	50	70
Demoulding time	-	hours	24 - 36	36 - 48

HANDLING PRECAUTIONS

Normal health and safety precautions should be observed when handling these products :
Ensure good ventilation
Wear gloves, safety glasses and waterproof clothes.
For further information, please consult the product safety data sheet.

STORAGE CONDITIONS

Shelf life is 12 months in a dry place and in original unopened containers at a temperature between 15 and 25° C.
Any open can must be tightly closed under dry nitrogen blanket.

PACKAGING

RESIN	HARDENER
EPO 4042 *2 x 5 kg* *1 x 10 kg*	*EPO 4042 – EPO 4042/L* *2 x 0.35 kg* *1 x 0.7 kg*

GUARANTEE

The information of our technical data sheet are based on our present knowledge and the result of tests conducted under precise conditions. It is the responsibility of the user to determine the suitability of AXSON products, under their own conditions before commencing with the proposed application. AXSON refuse any guarantee about the compatibility of a product with any particular application. AXSON disclaim all responsibility for damage from any incident which results from the use of these products. The guarantee conditions are regulated by our general sale conditions.

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LAB 1001

AXSON

LAB 1001

TOOLING BOARD
CHECKING FIXTURES
DENSITY 1.60 – CTE : 45.10^{-6} K^{-1}

APPLICATIONS

Checking fixtures
Stamping tools for non-ferrous sheet metals
Hammer forming tools

PROPERTIES

- *Excellent surface aspect after machining*
- *Low coefficient of friction allowing sliding*
- *High compressive strength*
- *Produces shavings (little dust)*
- *Gloss recovering*
- *Good dimensional stability*

PHYSICAL PROPERTIES		
Color	-	Off-white
Specific gravity at 23°C	ISO 2781-88	1.60

MECHANICAL AND THERMAL PROPERTIES AT 23°C			
Hardness	ISO 868-85	Shore D1 - D15	90
Compressive Strength	ISO 604-97	MPa	120
Charpy impact strength (unnotched specimens)	ISO 179/1D-94	kJ/m^2	10
Glass transition temperature	T.M.A.-Mettler	°C	100
Coefficient of linear thermal expansion (C_LTE) [+10, +80]°C	T.M.A.-Mettler	10^{-6}.K^{-1}	45

ASSEMBLY

Axson LAB 1001 tooling board can be bonded with S1 (about 900 g/m^2).

SAFETY PRECAUTIONS

Normal health and safety precautions should be observed when handling this product :

- *ensure good ventilation*
- *wear gloves and safety glasses.*

For further information, please consult the product safety data sheet.

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AXSON

LAB 1001

TOOLING BOARD
CHECKING FIXTURES
DENSITY 1.60 – CTE : 45.10^{-6} K^{-1}

MACHINING PARAMETERS		
	Cut speed (Cs in m/min)	Speed per rotation for 1 tooth (mm/tr)
Rough shape (1)	100	0.35
Finish (2)	400	0.06

(1) ***Roughing cut:*** *Cutting parameters are determined with a carbide inserts ball nose endmill;*
- *Helix angle: 6°*
- *Clearance angle: 14°*

(2) ***Finishing cut:*** *Cutting parameters are determined with a 2 teeth ball nose endmill:*
- *Helix angle: 30°*
- *Clearance angle: 14°*

STORAGE

The slabs must be stored in a dry place provided.

DIMENSIONS

830 x 500 x 100 mm
830 x 500 x 50 mm

GUARANTEE

The information of our technical data sheet are based on our present knowledge and the result of tests conducted under precise conditions. It is the responsibility of the user to determine the suitability of AXSON products, under their own conditions before commencing with the proposed application. AXSON refuse any guarantee about the compatibility of a product with any particular application. AXSON disclaim all responsibility for damage from any incident which results from the use of these products. The guarantee conditions are regulated by our general sale conditions.

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PROLAB 65

AXSON

PROLAB 65

POLYURETHANE MACHINABLE SLAB
MASTERS - PATTERNS - MOCK-UPS - PROTOTYPES
SPECIFIC GRAVITY: 0.65- HARDNESS 63 SHORE D

APPLICATIONS

Machinable slab designed for production of patterns, mock-ups, prototypes and masters by milling or machining by hand.

PROPERTIES

- *Non-porous material*
- *Excellent surface aspect (direct paint after sanding)*
- *Very good dimensionnal stability*
- *Machining by hand or by machine with wood cutting tools or aluminium cutting tools*

PHYSICAL PROPERTIES (1)		
Color	-	brown
Density at 23°C	ISO 2781-88	0.65

MECHANICAL AND HEAT PROPERTIES AT 23°C (1)			
Hardness	ISO 868-85	Shore D1	63
Coefficient of thermal expansion (CTE) [+10; +60]°C	T.M.A.-Mettler	$10^{-6}.K^{-1}$	75
Glass temperature transition	T.M.A.-Mettler	°C	85
Flexural strength	ISO 178-93	MPa	34
Flexural modulus of elasticity	ISO 178-93	MPa	1,000
Compressive stress at yield	ISO 604-93	MPa	28
Charpy impact resistance	ISO 179/1D-94	kJ/m^2	11

(1) Average values obtained on slabs

ASSEMBLY / FINISH

Axson tooling boards can be bonded with PROCOL 2 adhesive or A77/P mastic for small surfaces.

SAFETY PRECAUTIONS

Normal health and safety precautions should be observed when handling this product :

- *ensure good ventilation*
- *wear gloves and safety glasses*
- *do not smoke when machining.*

For further information, please consult the product safety data sheet.

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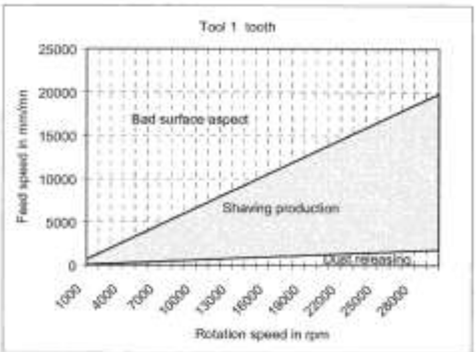
AXSON

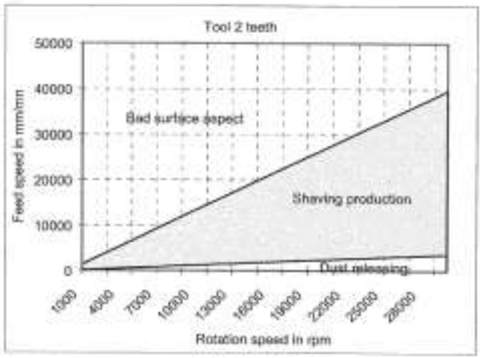
PROLAB 65

POLYURETHANE MACHINABLE SLAB
MASTERS - PATTERNS - MOCK-UPS - PROTOTYPES
SPECIFIC GRAVITY: 0.62 - HARDNESS 63 SHORE D

MACHINING PARAMETERS

Parameters determined with tools with positive angle of cutting and angle of taper.





MACHINING PARAMETERS (1)		
	Cut speed (Cs in m/min)	Speed per rotation for 1 tooth (mm/revolution)
Rough shape	100 to 500	0.15 to 0.70
Finish	400 to 800	0.07 to 0.10

STORAGE

The slabs must be stored in a dry place provided.

DIMENSIONS

- *850 x 500 x 30 mm*
- *1.550 x 500 x 50 mm*
- *1.550 x 500 x 75 mm*
- *1.550 x 500 x 100 mm*

GUARANTEE

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