

Learning Beyond the Classroom – Our Experience of Making a Vacuum Forming Mould at Hethel Engineering Centre

Written by

Steven Daly

Head of Design and Technology at Langley School, Norfolk and
Education Advisor to The Hethel Centre

sdaly@langleschool.co.uk

Derek Hillyard

Engineering Manager
The Hethel Centre

Norfolk

dhillyard@hethelcentre.com

Terminology

In this report the word mould and former refer to the same thing – a part you use to vacuum form over.

Formings are the actual vacuum formed parts.

Introduction

This report is primarily about the design and manufacturing of a mould for a vacuum formed project which was undertaken by Derek Hillyard at Hethel Engineering Centre (www.hethelcentre.com) and me, Steve Daly at Langley Independent School (www.langleschool.co.uk). It also provides a great opportunity to introduce, what is intended to be, Norfolk's or even East Anglia's, Centre of Excellence in Design, Technology and Engineering. The Hethel Engineering Centre has extensive resources which can be accessed by local schools. This includes a 3D Printer (Z Corp powder based system which is later described). The machine can make parts very quickly and cheaply with what can be described as a sand cast finish. Derek and I wanted to know how far we could push the machines boundaries (materials, tolerances and accuracy) by making a 'tool' as opposed to just a pretty model. We also want to get involved in using the machine to make moulds for cold (polyurethane) and hot casting (using Z Cast Powders). The mould which would be designed and manufactured using this process would be tested by Langley Prep School (Primary School) year 3 – 6 during an after school club making toy yachts. The yachts would also be used during a science lesson to provide children the opportunity to design and make sails of different shapes and test them in a water filled tank and a high powered fan. I decided to design the mould and Derek would show me how to RP (Rapid Prototype) it on the Z Corp machine. Once made the mould would be post processed using epoxy resin to add vital strength as well as sealing the former from moisture. With this in mind, this report discusses the process of designing a product (toy yacht), creating a former using the Z Corp machine and then testing its performance. The yacht, designed using Solidworks 2007, notes on mould design and vacuum forming (Courtesy of CR Clarke) can be downloaded from the DATA website – ([Willy, need hyper link](#)). The CAD file is also supplied in IGES format to allow you to import it into another CAD package.

Introducing The Hethel Engineering Centre

Hethel already has extensive facilities, resources and expertise in engineering, manufacturing, rapid prototyping and links with industry providing an extensive localised knowledge base. More importantly it is a centre which is seen as locally 'neutral', not biased towards any given institution and is open to work with any local school that would benefit from it. The centre will eventually provide important access for schools to its extensive resources, act as a forum, provide a centre for professional development for teachers (primarily focused on Design, CAD and CAM) and eventually localise all D&T activity. Hethel will also extend this network to other centres of excellence, for example, CEME (Centre of Excellence in Manufacturing and Engineering, based in Dagenham) who have a very successful D&T section which provides support to Havering, Barking and Dagenham, and of course our national representative - DATA (Design and Technology Association).

Figure 1. The Hethel Engineering Centre

Mould Design

Encapsulated Moulds

A number of decisions need to be made before designing your vacuum forming mould. For example, will the product you are making be a one-off? If it is, then can it be encapsulated (the mould remains inside the formed part)? Packaging is sometimes made using this process. Encapsulated parts don't require draft angles and the mould can offer the part much needed strength.

Part Encapsulated Moulds

Are there any potential parts of the product which could become encapsulated? If so it may be a requirement that this part of the mould becomes detached and remains inside the formed part after vacuum forming. A new detached part can be made and added to the main mould using pins/dowels ready for vacuum forming. This allows you to repeatedly use the main part of the mould over and over again and only make the detached part.

Non-encapsulated Moulds

The forming, shaped by the mould, should not have any parts held within its body. These are the most common types of moulds made in schools. This is the type of mould which will be used for making the toy yacht.

Draft Angles and Filleted Edges

All moulds used for processes like vacuum forming, injection moulding, die casting type processes require draft angles to enable the forming to be released from the mould once formed. The general rule is that the draft angle should be 2 - 3° but can be as low as 0.5°. Draft angles are applied to all surfaces which are parallel to the direction the forming is pulled to release it from the mould, see figure 3. The mould should have all geometry which makes contact with the thermoplastic sheet filleted (radius applied to edges). Fillets should be at least 1mm. If your mould is made from a coarse material then it is advised that the draft angles and fillets are increased to aid the release of the forming.

Thinning Effects in Cavities

One of the most common problems in the design of vacuum formed products is thinning. Different mould shapes present different thinning problems. The depth of a forming is limited by the ability of the material to stretch into a long deep shape. Figure 2. The effects of deep cavities have on wall thickness. We can apply this to a simple hole, perhaps one which is used to hold the mast of the toy yacht. Ordinary vacuum forming machines generally vacuum form material to a depth of about half the diameter of the size of a hole. If you want a deep hole you need to ensure that the diameter of the hole is at least twice the depth of the hole. Filleting the corners at the bottom will improve the depth. Rounding the bottom completely will treble it. Figures 6, 17 and 23 are good examples of problems with hole diameter and depth.

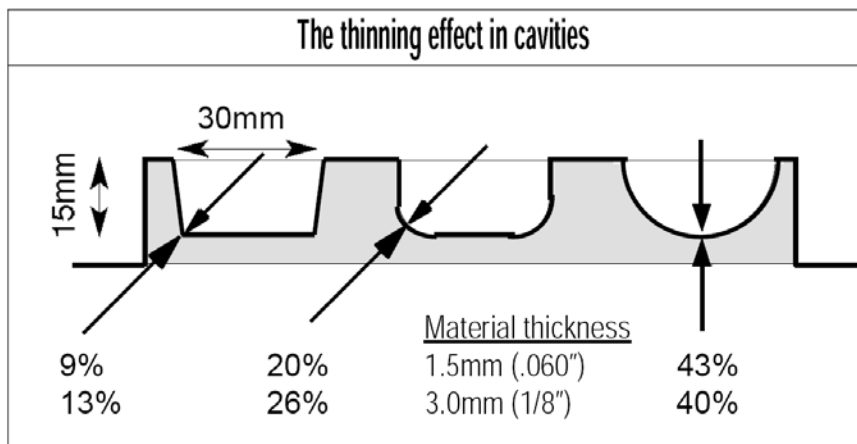


Figure 2. Thinning effects in cavities
(Courtesy of CR Clarke)

If the hole is too deep the material at the bottom becomes so thin it is unusable. Cups and yogurt pots are made with machines that have a male mould, commonly referred to as a plug, which pushes the heated material into a female mould/former before the evacuation of air (vacuuming) commences. This distributes the material more evenly over the mould thus achieving deeper draws.

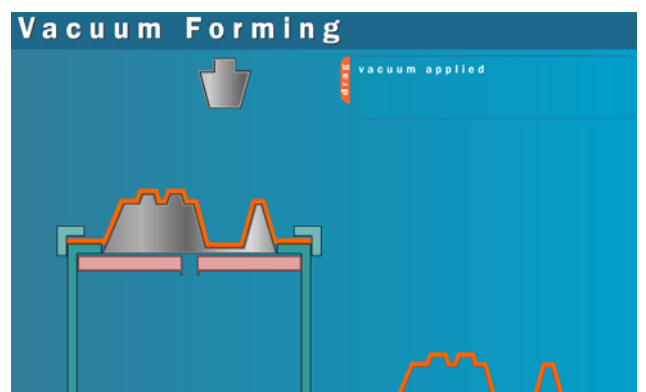
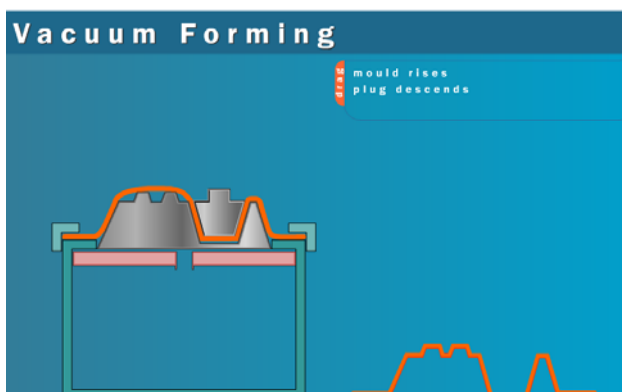


Figure 3. Using a plug to aid deep cavities when vacuum forming
(http://www.bpf.co.uk/bpfindustry/process_plastics_vacuum_forming.cfm)

Thinning Caused by the Cooling of the Material

As soon as the heated sheet makes contact with the mould, it will start giving up its heat to the mould and becoming rigid again. This is why it is common to find a forming (formed plastic part) with a greater material thickness at the highest point of the forming, compared to the lowest, hence the material which makes contact with the mould first, cools, does not stretch and become thinner. The material which makes contact last will have stretched and become thinner.

Checking for Thinning

By drawing a grid on a thermo plastic sheet before vacuum forming you can show where the areas of thinning are occurring. To reduce thinning you could modify the former or reduce the heat in that area of the thermo plastic during the vacuum forming process.

Webbing

Webs will form between points that are too high and/or too close together. As the material is drawn down it meets itself and forms a fold before it comes into contact with the mould. The use of a male mould or a grid can prevent webbing by distributing the plastic evenly and preventing it from meeting itself. Figure 16. is a good example of the problem of webbing due to the height and shape of the keel.

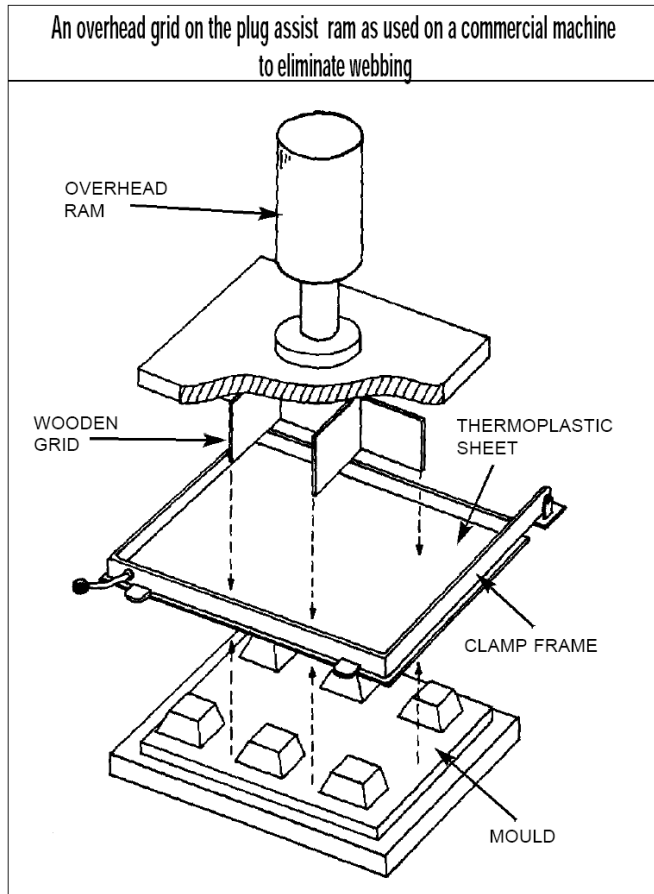


Figure 4. A grid which can be used to prevent webbing
(Courtesy of CR Clarke)

Materials

Moulds for vacuum forming are most commonly made from timber products, aluminium, epoxy resin, polyurethane modelling board (very good but expensive). Other materials such as steel, copper, brass, MDF, paper, card, glass, thermosets like 'Bakelite' (Urea formaldehyde), plaster of paris, dental plaster, clay or plasticine can be used on their own or in combination.

Stage One -Design the Yacht and Mould

An important point to consider before you design your mould is whether you will make a single part, for example the yacht body, and then split it (hull and deck) or whether you will make two separate parts and assemble them and check they mate correctly. I recommend designing a single part and then splitting this into two parts. This ensures a perfect mate between the parts and also makes it easy to adjust the shape of the model before it is split. You must then find out your vacuum forming machine envelope. This is the size of the mould which your machine is capable of forming over. This will ensure that you don't exceed the machines capabilities.

Figure 4a is an example of an injection moulded bird feeder which was designed as a single part with all the required features except the perches and the locating dowels. It includes the thread which matches the thread of a PET bottle. The main body was designed as a single part and then split into two parts using a work plane (right) creating two solid bodies.

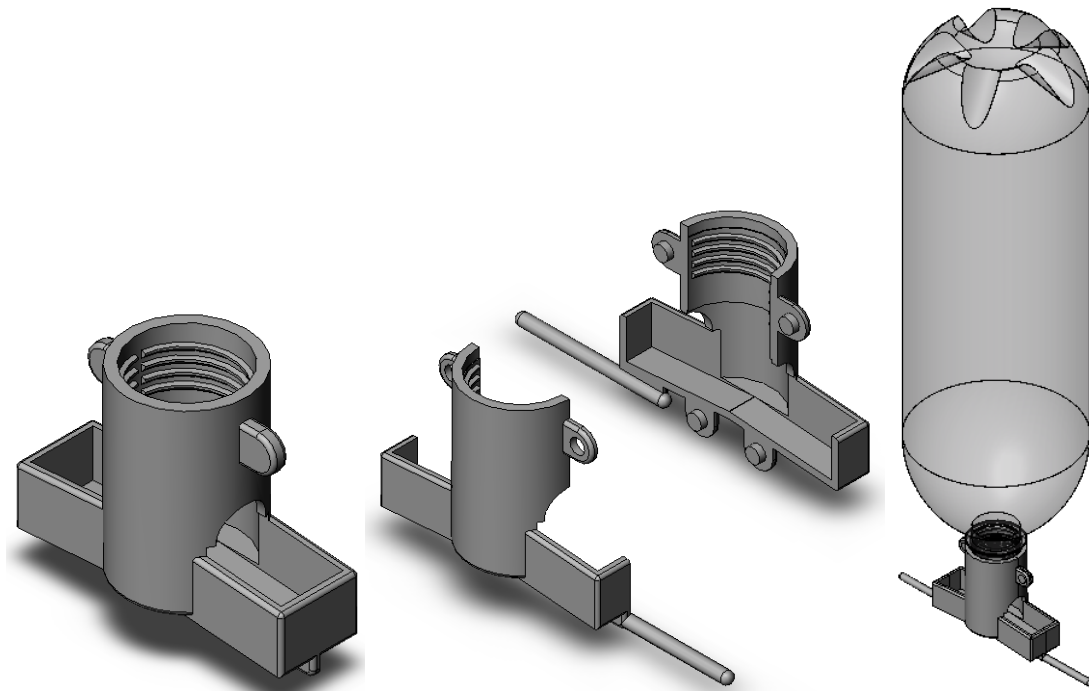


Figure 4a. A single part which was modelled and then split into two parts and assembled.

Important note

If you make a mistake with the size of the mould you can use CAD software to scale your mould to fit. Use the help menu within Solidworks to find the 'Scale' option. Remember if you scale your mould, you may need to adjust certain critical dimensions, like diameters of holes which accommodate the mast and sail adjuster.

This report does not have the space available to provide a step-by-step description of how the yacht body was designed in Solidworks. The yacht assembly is available for download from the DATA website which will enable you to uncover the very simple combination of geometric features which were used to produce the body. This report will describe some important aspects of mould design, analysis, manufacturing, testing and development/enhancement for performance.

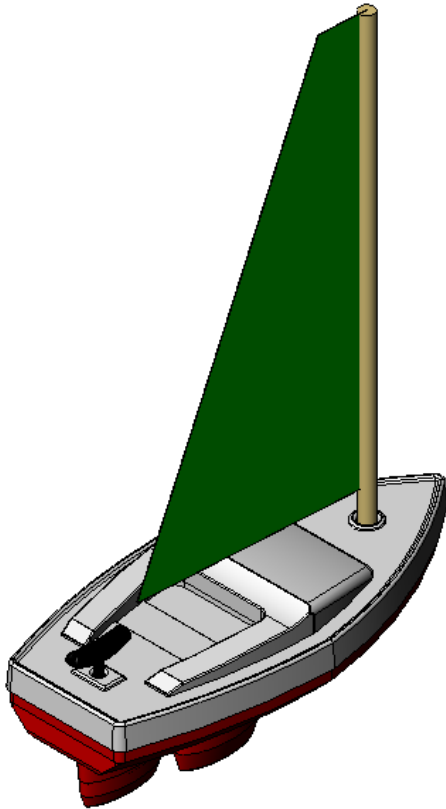


Figure 5. Toy Yacht (Original Design)

The yacht assembly includes a deck (top section shown in white) and a hull (shown in red) with a double keel which is a common feature on toy yachts to assist with directional control. The deck holds the sail adjuster at the stern of the yacht (black adjuster which tensions the sail fitted at the rear of the yacht) and the mast for the main sail.

Figure 6. shows a section view of the body of the yacht and how shape plays a critical role when designing a locating hole which is used to support the mast. You can see how circular ribs which have been added to the top of the hole and the outer body are used to provide strength. These ribs add much needed rigidity to thin walled plastic. The bottom of the hole has a large radius to maximise the thickness of the wall of the material which forms the hole. The diameter of the hole must be matched against the size of the mast (ramin dowel) plus the thickness of the material which will be formed inside it. For example, if the ramon dowel for the mast is 6 mm and the vacuum forming material is 1.0mm thick then the hole in the mould should be 7mm. The draft angle for the hole is small, only 2° (can be as small as 0.5°) otherwise it will restrict the depth of the hole by greatly altering the diameter. The draft angle for the hole can be small due to the small surface area and low potential force which the hole would cause in restricting the removal of the forming.

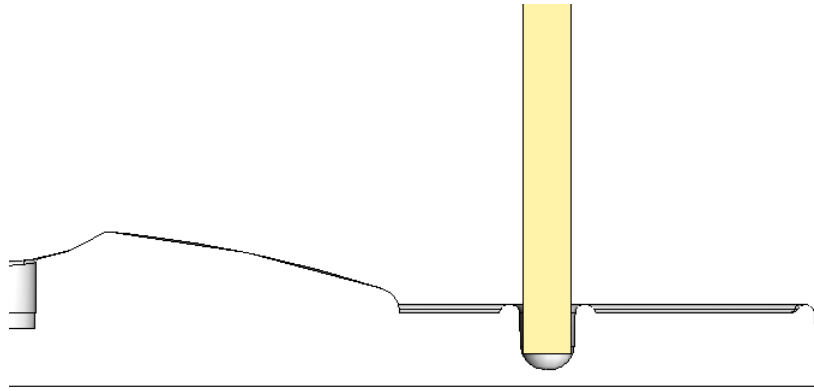


Figure 6. Section view which shows the hole where the mast is located

Parting Face

A key consideration which is required to make this yacht is the parting face (where the two parts should meet/part). You will need to split the body of the yacht into two parts to create your mould (tool). The parting face is shown in figure 7. where the red hull meets the white top section of the yacht. This conveniently coincides with the top work plane which can be used to separate the part. This parting face was used to ensure that the faces of the two parts meet above the predicted water line of the boat.

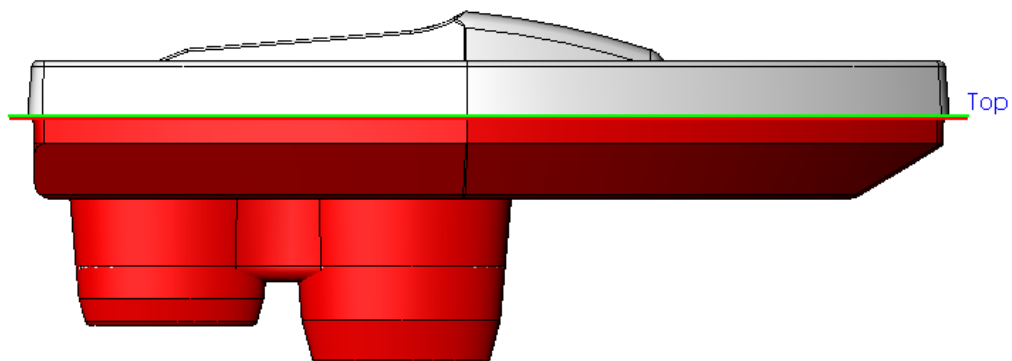


Figure 7. Parting the yacht body using the top work plane

The body of the yacht has now been split into two parts. These can be mounted on a base (5mm thick, 10° draft) to create the mould (tool) which will form the hull and deck of the yacht.

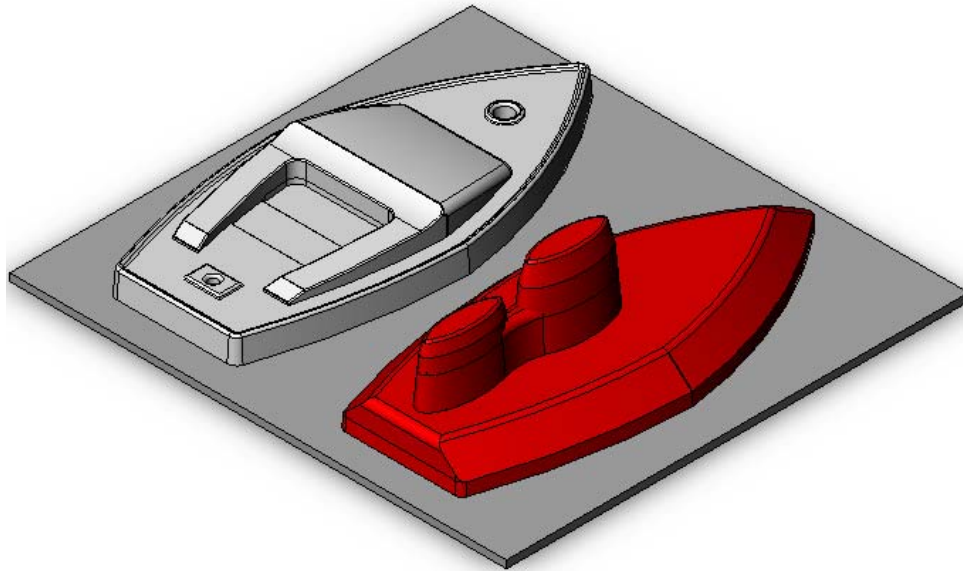


Figure 8. Mould assembly development (stage one)

Adding Evacuation Holes

Holes can be incorporated into the design and manufacture of the mould using the ZCorp 3D Printing Process. Due to the machines accuracy they must be at least 1mm in diameter, preferably 1.5mm. Holes should be positioned where air may become trapped, any large flat surfaces, corners and geometry which have a deep cavity. Holes were not added to this design because the former will be treated with epoxy resin to enhance its strength. Applying epoxy resin to a mould with very small holes would potentially reduce their diameter or close them off, so holes are drilled into the mould after it has been treated.

Important Note

You would normally check the design using draft analysis before you create the mould assembly. The yacht body and the mould assembly will have file bi-directional associatively. This simply means that if you adjust the geometry of the yacht body then the mould assembly will update itself, likewise if you adjust the mould assembly then the yacht body will update itself.

Stage Two – Testing the Former Before Manufacture

Draft Analysis Checks Using Solidworks

Designers of moulds can use the ‘Draft Analysis Tool’ within Solidworks to check the correct application of draft to the faces of their part. With draft analysis, you can verify draft angles and examine angle changes within a face to ensure the part can be released from its mould. Draft analysis is also a useful tool to include in the

development section of a student's portfolio providing evidence of how the mould was checked prior to manufacture.

Draft Analysis on the Base of the Yacht

Two parameters are required to carry out a draft analysis on the base of the yacht. The first is the pull direction of the forming, in other words, the direction you will remove the vacuum formed part. I have selected the top, because the plastic will be formed over the top of the former and then removed by pulling up. The second parameter is the minimum draft angle of the mould (yacht hull); due to the rough surface texture of the rapid prototyped mould I have decided to set all draft faces at a minimum of 5 degrees.

A 5 degree draft angle parameter is put into the draft analysis. The results are provided through the use of colour on the model showing you exactly where changes must be made – green shows acceptable draft angle, red shows a negative draft angle and yellow shows insufficient draft angle.

The following faults were identified on the model in yellow: - draft angle on the stern (rear) has been missed and a greater draft angle is required on the back of the keel and the sides of the yacht base.

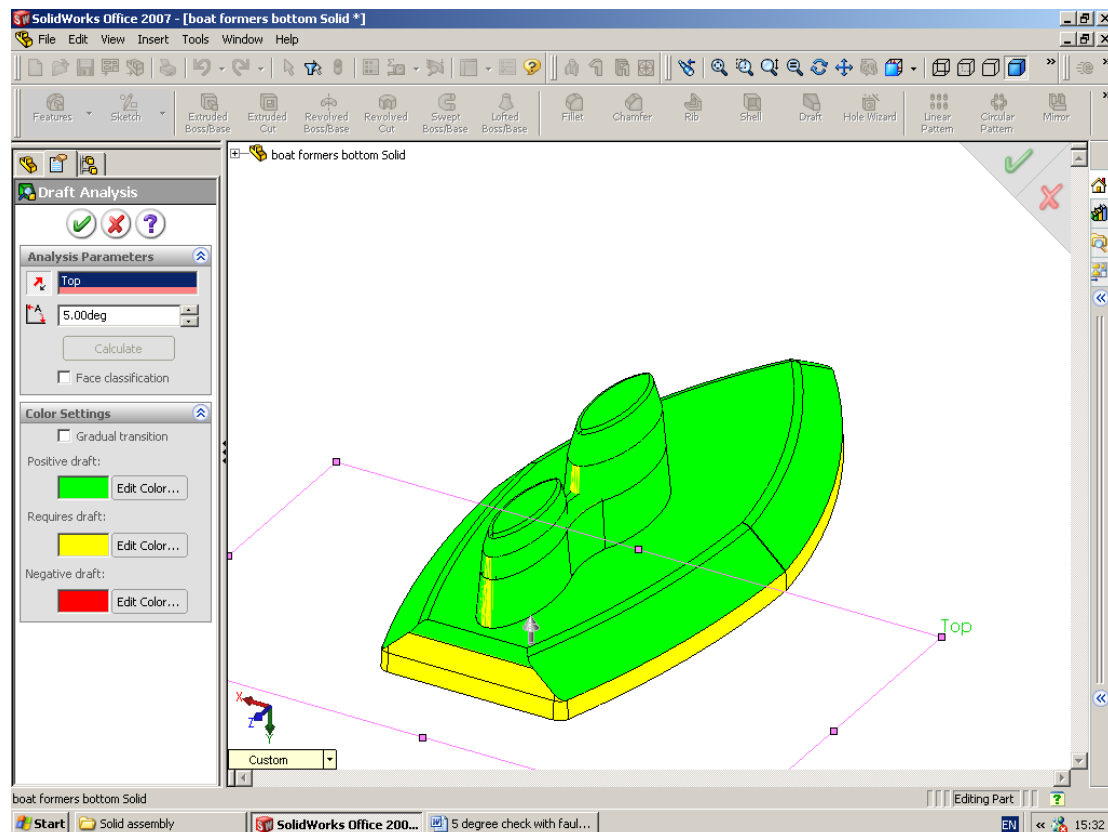


Figure 9. Draft Analysis on yacht hull using Solidworks

Draft Analysis on the Deck of the Yacht

Again, a 5 degree draft angle parameter was entered into the draft analysis tool and then processed.

The following faults were identified on the model in yellow: - draft angle on the sides of the cabin and holes have insufficient draft angle.

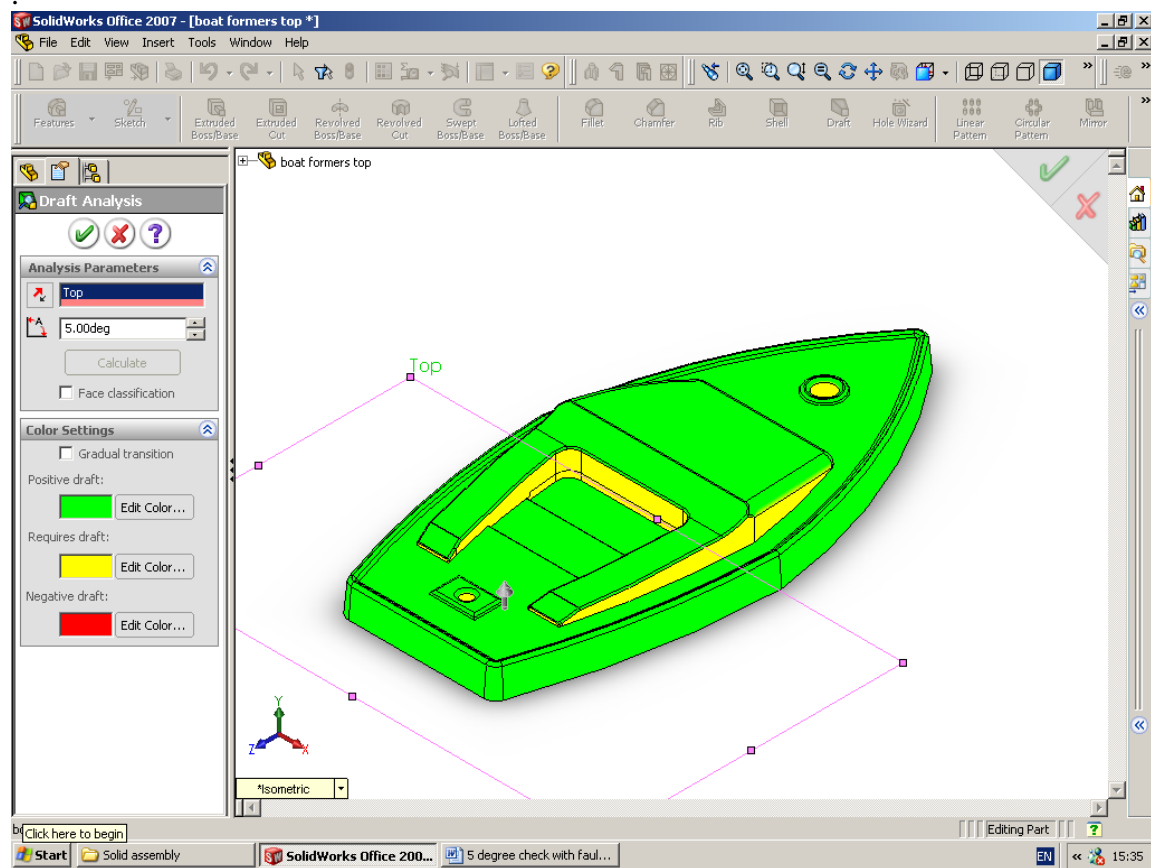


Figure 10. Draft Analysis on yacht deck using Solidworks

A draft angle was added to the stern (back) of the yacht. Other key draft angles were changed to ensure that there was no yellow highlighted areas on the mould when the draft analysis was reapplied (except for the holes for the mast and sail adjuster).

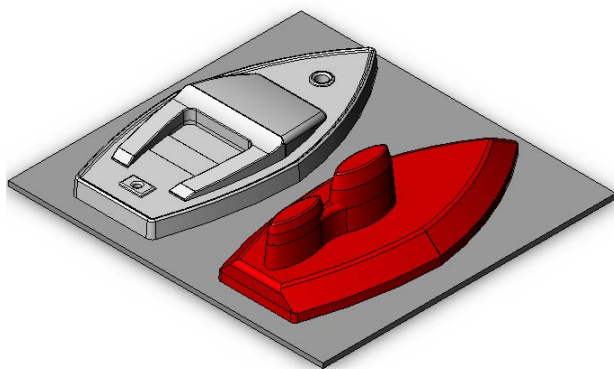


Figure 11. Solidworks assembly of the mould

The assembly was converted to an STL file* and sent to Derek at the Hethel Engineering Centre.

***Note**

STL is a file format native to the stereolithography CAD software created by 3D Systems. This file format is supported by many other software packages; it is widely used for rapid prototyping and computer-aided

manufacturing. STL files describe only the surface geometry of a three dimensional object without any representation of colour, texture or other common CAD model attributes. The STL format specifies both ASCII and binary representations. Binary files are more common, since they are more compact.

Manufacturing the Mould

I visited Derek at the Hethel Engineering Centre and he showed me how to make the mould using the Z Corp 3D printing Process on a Spectrum Z510 (colour) printer. The machine uses a plaster based material which is bound together using a water based ink and binder mix which is applied via standard inkjet cartridges. The resulting parts can be infiltrated with other materials to increase their strength and durability.

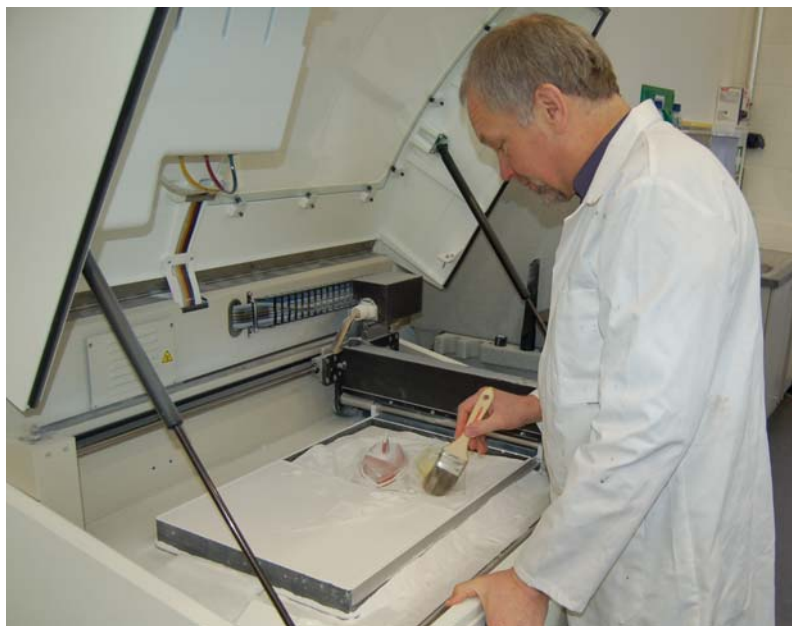


Figure 12. Derek is brushing excess powder off the mould

Explanation of the Z Corp RP Process

The Z Corp printer accepts solid models in STL, WRL, SFX and PLY file formats. In this case the STL file format from Solidworks was used and the solid part loaded into the printer software. The software is equipped with 3-D viewing, labelling and scaling functionality and you can select different colours, add text and even apply photographic images to surfaces. Once satisfied with the visual appearance the part gets transformed from a 3-D image into a 3-D solid part.

Function of the Printer

There are two chambers within the Z Corp printer. A feed chamber filled with the powder on the left, and a build chamber where the actual part is made on the right. The build chamber drops slightly while the feed chamber lifts slightly. A roller spreads a fine layer of powder 0.1mm thick across the build side which is sufficiently fine to give a 'staircase' free surface finish. Then the inkjet printer head applies a binding liquid on the cross-section of the part where it solidifies the powder. Solidification only occurs where the binder makes contact with the powder. The roller

returns to the powder chamber where it lifts as the build chamber drops and the process of spreading a layer of powder and applying the binding liquid repeats until the part is complete. When the part is finished it is buried in the powder. The build chamber is lifted up and powder, not bound together, is brushed back into the feed chamber. The final clean-up of the part is performed and all unused powder is recycled to be used again.

HOW IT WORKS

- Software "slices" CAD file into thousands of thin layers
- Physical model is built one layer at a time
- Ink-jet print heads deposit binder into powder to create layers

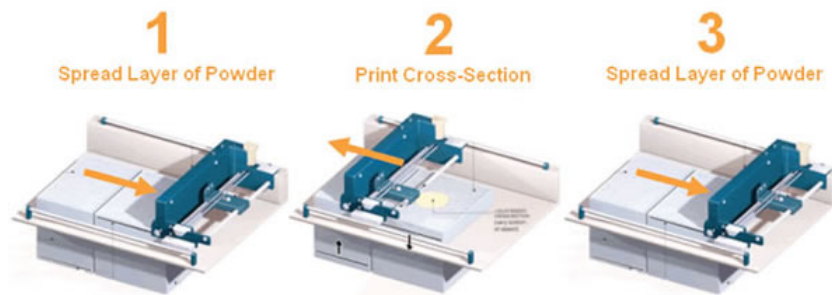


Figure 13. Function of a 3D Printer

Preparing the Former

Once the mould has been printed, it is about 50% porous and can be infiltrated to produce a range of material properties. Infiltrant options include a variety of waxes and resins depending on the desired part characteristics. I highly recommend painting epoxy resin on the printed moulds which are going to be used for vacuum forming. This seals the surface and gives the part sufficient strength to enable it to be used for vacuum forming. The surfaces can be sanded down with fine emery paper and a coating of silicone can also be applied to assist with easy removal of the forming.



Figure 14. 3D printed mould

Testing the Mould

Problems with Releasing the Mould

The mould was taken to Langley School and a number of yacht bodies were made to test the performance of the mould and the fitment of the mast and sail adjuster. The formings were not quite as easy as they should be to separate from the mould. An experienced user of the vacuum forming machine was able to separate the forming with a little bit of force. However, when the students used the mould they found it more difficult to separate the mould from the formings. In view of these difficulties, I decided to change the draft angles on the yacht sections to a minimum of 10° and increase filleted edges on the boat hull to 2mm.

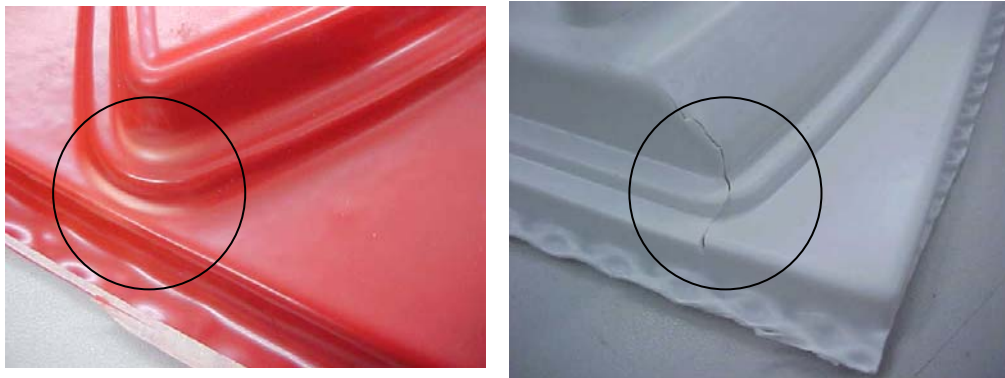


Figure 15. Failure - stress marks and splitting due to force required to separate mould and forming.

Problems with Webbing on the Keel

Webbing occurred due to the geometry of the keel. Either the keel needed to be modified or a plug and grid would have to be designed to distribute the plastic evenly over the mould before evacuating the air. I decided to change the keel geometry to stop the possibility of webbing occurring. If this reduced the performance of the yacht then I would make use of the original mould but with a grid to distribute the plastic.



Figure 16. Failure - webbing due to the material of the forming overlapping

Changes to the Hole which Locates the Adjuster

The diameter of the hole which is at the stern of the yacht was increased to enable the plastic to be drawn deeper into the hole. The diameter of the hole should be at least double the diameter of the depth which is required. This will enable the adjuster to be located.



Figure 17. Failure – hole not deep or large enough to be formed for the sail adjuster

Adjustments to the CAD Model (Solidworks)

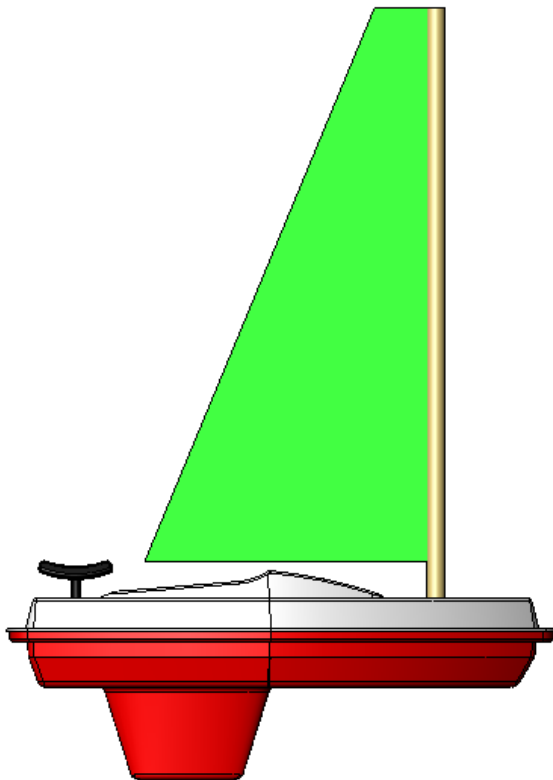


Figure 18. Toy Yacht (Modified Design) using Solidworks

Final Solidworks Design

The keel was adjusted, as shown in figure 18, to reduce webbing and allow for the easy removal of the forming. The yacht was reanalysed using Solidworks Draft Analysis and all identified geometry with a draft angle below 10° was changed. Fillets on the hull were increased from 1mm to 2mm to also aid removal of the forming from the mould. A lip was added to the bottom of the top section (deck) and the top of the hull. This was added to assist students by giving them a good surface area to apply an adhesive when joining the two parts together.

Solidworks Final Draft Analysis

You can see in figure 19 and 20, the draft analysis shows that both the hull and the deck have no yellow sections except where the holes are for the mast and the sail adjuster. This means that the model has minimum draft angles of 10° or more. These new draft angles should help with removing the forming.

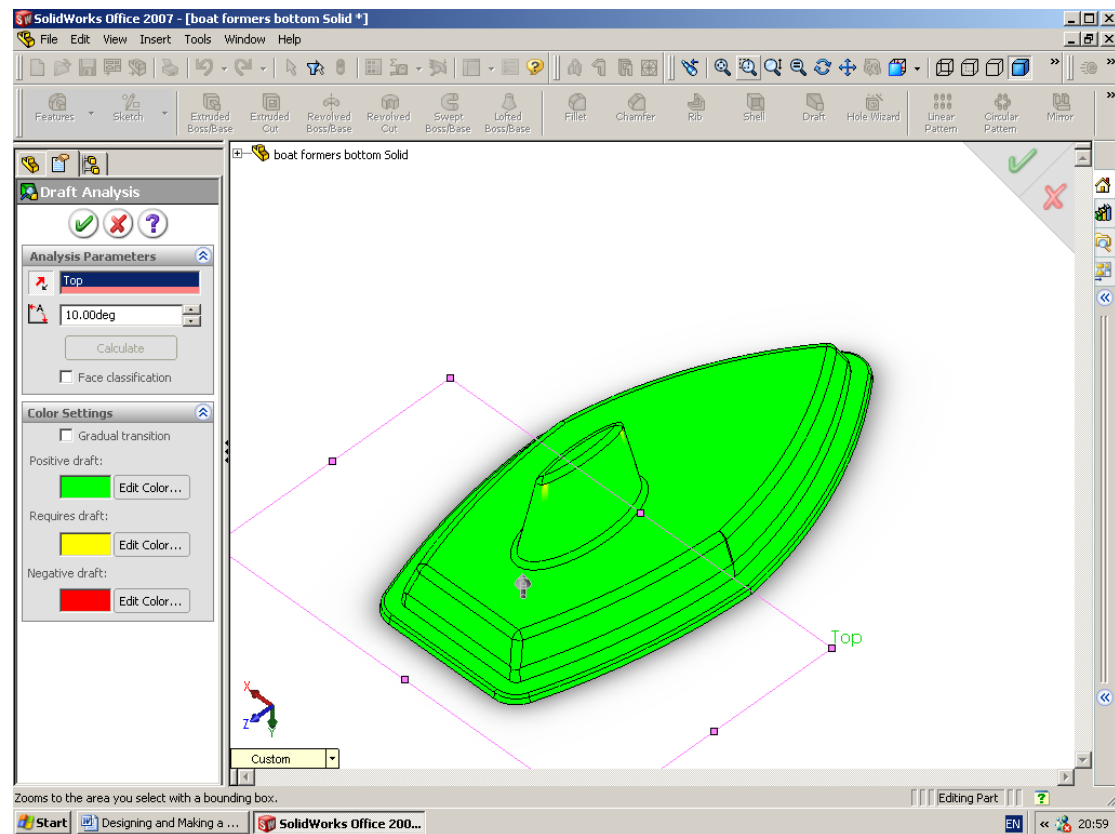


Figure 19. Second draft analysis applied to the yacht hull using Solidworks

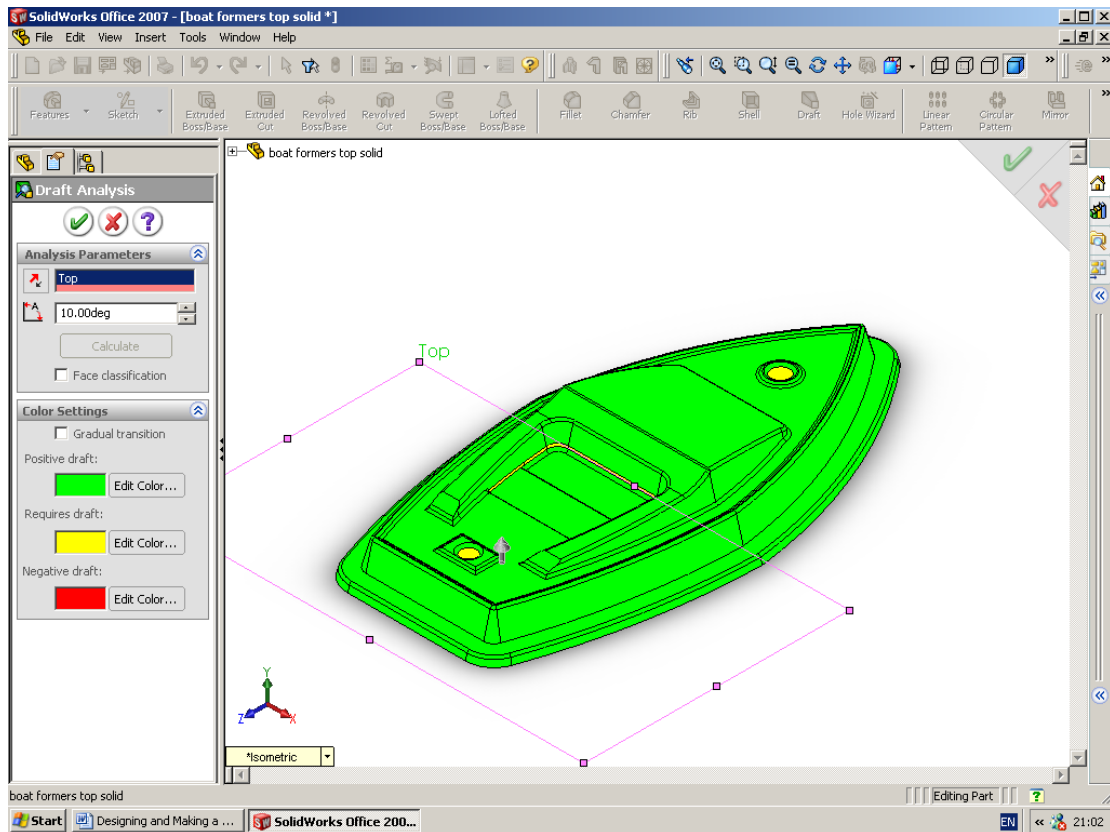


Figure 20. Second draft analysis applied to the yacht deck using Solidworks

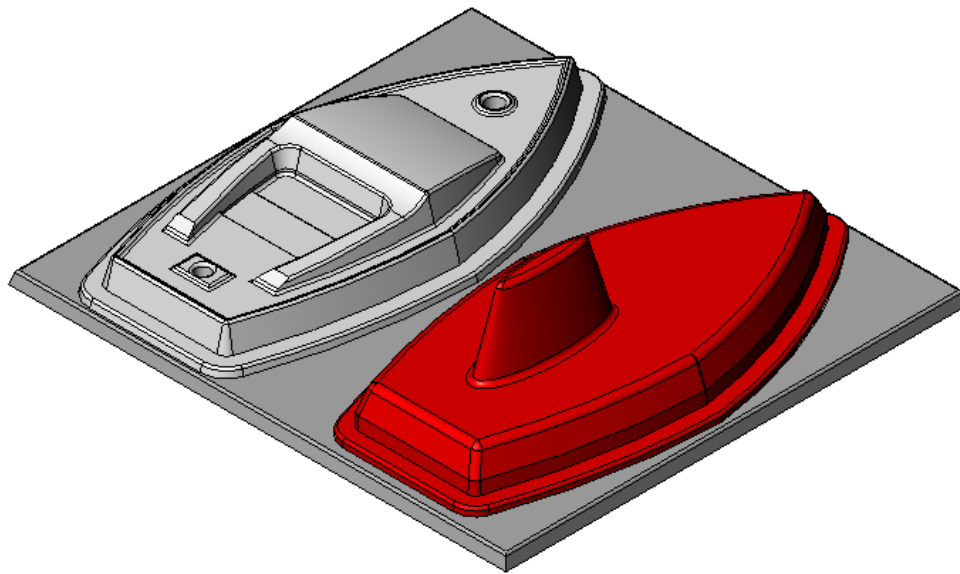


Figure 21. Solidworks assembly of the modified mould

The new mould was manufactured at Hethel and tested by the Students at Langley School. The new draft angles and increased filleted edges made it very easy to remove the forming so no stress marks or splits in the material occurred. The increase in the diameter of the hole for the adjuster which is used to tension the sail has also improved the hole in the forming, see figure 23. The mould has currently made about 40 yacht bodies without showing any issues of reliability or failure. The students add

ballast to the keel, cut the mast from Ramin Dowel, design and make the sail and we provide the adjuster.

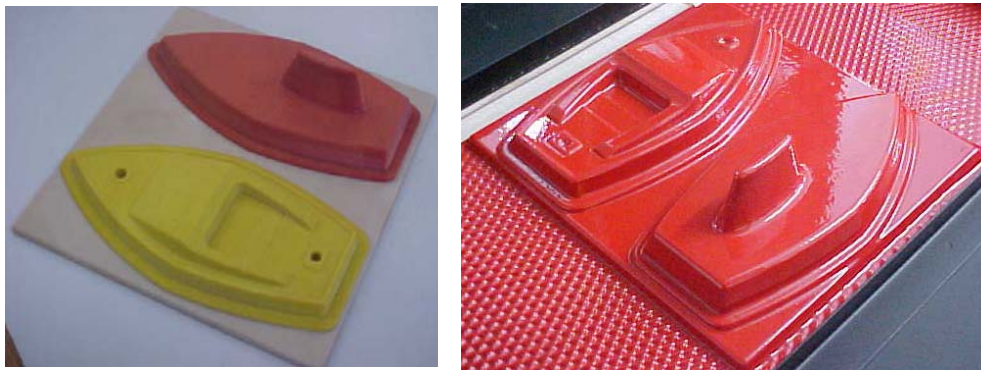


Figure 22. RP of mould and a forming.



Figure 23. Improved locating hole for the adjuster.

Final Note

When using a Z Corp machine for making moulds for vacuum forming or cold casting large draft angles and fillets are required to enable the removal of the forming/mould due to the rough (sand casting like) surface texture. The material is cheap and the moulds are made very quickly (2 hours). This machine may find good use within a network of schools within a borough.

Hethel and Langley are now developing moulds to be used for hot casting and will publish their results next year.

Acknowledgements

A big thank you to the following companies who assisted with this report by providing resources for this article.

CR Clarke
EMCO
The Hethel Engineering Centre