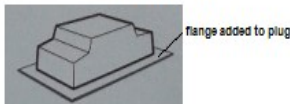


## CHAPTER 2: LITERATURE STUDY

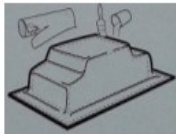
The classical composite manufacturing process consists of three basic elements: the manufacturing of the positive master called a plug, the manufacturing of the negative mould, and lastly, the manufacturing of the required component. The part is created from the mould and the mould itself is created from a plug. The plug is the part with an added split surface. Figure 2-1 explains this process (Wanberg, 2009).

Class A finished composite parts can only be obtained from moulds with a Class A surface finish which, in turn, can only be produced from plugs with a Class A surface finish, as illustrated in Figure 2-2.

1. Create a smooth plug surface



2. Layup composite tooling over plug



3. Demould composite tooling from plug



4. Create a part in the new mould



5. The demoulded part will be the exact size and copy of the original plug



**Figure 2-1: Creation of a plug and mould (Wanberg, 2009).**

An additional requirement for moulds is that they should be durable and last for a specified minimum number of production cycles. This requirement can be accomplished by using the proper mould manufacturing techniques. This literature study will investigate both the definition of Class A composite parts, as well as techniques on how to obtain durable plugs and moulds.

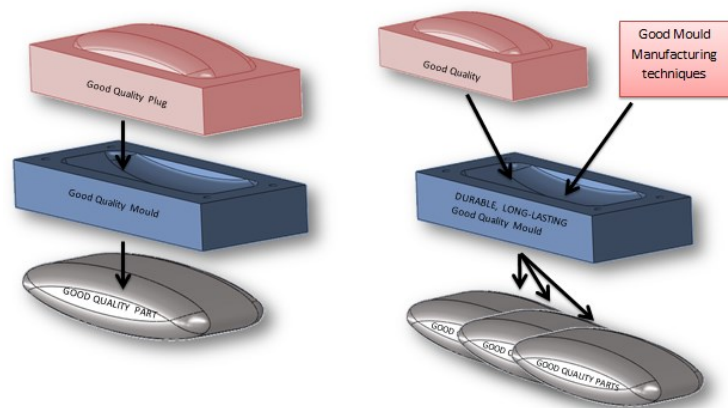


**Figure 2-2: Obtaining multiple Class A finished parts.**

## 2.1 CLASS A FINISHING: A DEFINITION

The term used to describe the acceptable surface roughness for exterior car body panels in the automotive industry is known as Class A surface finish. This term has, however, not yet been defined for the composite industry. If a surface which is made of a composite material has an optical appearance identical to an adjacent steel panel, which is Class A, then it can be said to be Class A. For purposes of the current study, it is therefore necessary to define what is meant with Class A finish in the metal industry, which will enable one to develop a suitable definition for the composite industry (Raja, 2005).

Surface finishing can be divided into three classes denoted A, B and C. In the automotive industry these classes have the following meanings, which are also dependent on the location of the part (Catia, 2012):

- ◆ **Class A:** Any surface that the customer sees, such as the exterior panels of doors, wings and the like.
- ◆ **Class B:** Any surfaces that are not always visible, but which could be seen if exterior panels are, for instance, bent down – these would include the underside of a fascia.
- ◆ **Class C:** Surfaces that are situated at the underside of a part which is permanently installed or covered by another part.

The plastics industry uses a different approach towards defining surface finishes. The Society of the Plastics Industry (SPI) has established the standards of surface finishing for this industry. One of the standards set out by this society is to define the degree of polish on the inner surfaces of the plastic that is used to form product moulds. These standards specify 12 grades of mould finishes, with ranges from mirror-perfect to dull. Table 2-1 is a summary of these grades (Catia, 2012; The Mould Polishing Co. Inc., 2012; Kirchoff, 2011).

**Table 2-1: Summary of surface finishing grades**  
**Catia, 2012) (The Mould Polishing Co. Inc., 2012; Kirchoff, 2011)**

| Class           | Location of a typical part                                                                                            | Compared Metal mould finish | Plastic part finish                                                                     | Deviation from perfect [millionth of an inch*] | Displacement SPE standard** |
|-----------------|-----------------------------------------------------------------------------------------------------------------------|-----------------------------|-----------------------------------------------------------------------------------------|------------------------------------------------|-----------------------------|
| <b>Class A1</b> | Any surface that the customer sees, like exterior panels of doors, wings etc., plastic mirrors, optical plastic goods | grade #3 diamond buff       | - Shiny<br>- High-gloss finishes<br>- No mould parting marks or tool or machining marks | 1                                              | SPE #1                      |
| <b>Class A2</b> |                                                                                                                       | grade #6 diamond buff       |                                                                                         | 2                                              | SPE #2                      |
| <b>Class A3</b> |                                                                                                                       | grade #15 diamond buff      |                                                                                         | 3                                              | -                           |
| <b>Class B1</b> | Any surfaces that are not always visible, but could be seen if exterior panels are, for instance, bent down.          | 600 grit paper              | - Semi-gloss with some sheen<br>- No mould parting marks, or tool or machining marks    | 3                                              | -                           |
| <b>Class B2</b> |                                                                                                                       | 400 grit paper              |                                                                                         | 5                                              | -                           |
| <b>Class B3</b> |                                                                                                                       | 320 grit paper              |                                                                                         | 10                                             | SPE #3                      |
| <b>Class C1</b> | Surfaces which are situated at the underside of a part which is permanently installed or covered by another part.     | 600 stone                   | - Matt<br>- No mould parting marks, or tool or machining marks                          | 12                                             | -                           |
| <b>Class C2</b> |                                                                                                                       | 400 stone                   |                                                                                         | 28                                             | -                           |
| <b>Class C3</b> |                                                                                                                       | 320 stone                   |                                                                                         | 42                                             | SPE #4                      |
| <b>Class D1</b> | Die-cast or thermoset plastic industrial parts                                                                        | dry blast glass bead #11    | - Dull<br>- Non-reflective finishes                                                     | 12                                             | -                           |
| <b>Class D2</b> |                                                                                                                       | dry blast #240 oxide        |                                                                                         | 32                                             | SPE #5                      |
| <b>Class D3</b> |                                                                                                                       | dry blast #24 oxide         |                                                                                         | 230                                            | SPE #6                      |

\* 1 inch = 25.4mm  
 \*\* "The Society of Plastics Engineers (SPE) from the 1960s through 1980s offered a scale of 1 to 6 to specify mould finishes ranging from a high-sheen diamond polish to rough blasted surface. The SPI incorporated the SPE grades in its new finishing standards"(Kirchoff, 2011)

From Table 2-1 it can be seen that Class A1, A2, and A3 surface finishes are high-gloss finishes which have no mould parting lines and no machine marks. These can further be compared to sanding finishes with that are achieved using sanding paper with a grit higher than P600. Paint, or gelcoat layers, can be finished to grit of 1200 or 1500 (Aiken & Aiken, 2012). Since this number is higher than a P600 grit, it could thus be concluded that Class A finishing of composites refers to:

- Finishing of anything using 800 to 1500 grit sanding paper
- No mould parting lines
- No machine marks, and
- Shiny and high gloss.

From here onwards, this type of finishing will be understood as a Class A surface finish. However, in order to verify that the quality of a surface is indeed Class A, it should also be measured.

## 2.2 MEASURING OF SURFACE QUALITY

The finish of a surface is a quality characteristic which has three components: lay, surface roughness and waviness (Degarmo *et al.*, 2003).

Lay refers to the direction of the predominant surface pattern which is usually determined by the production method used (Degarmo *et al.*, 2003).

Waviness, in turn, is the measure of surface irregularities with spacing greater than that of surface roughness. This surface roughness is a measure of the finely spaced surface irregularities. In engineering, this is what is usually meant by "surface finish". These terms are explained in Figure 2-3 (Mike, *et al.*, 1998-1999).

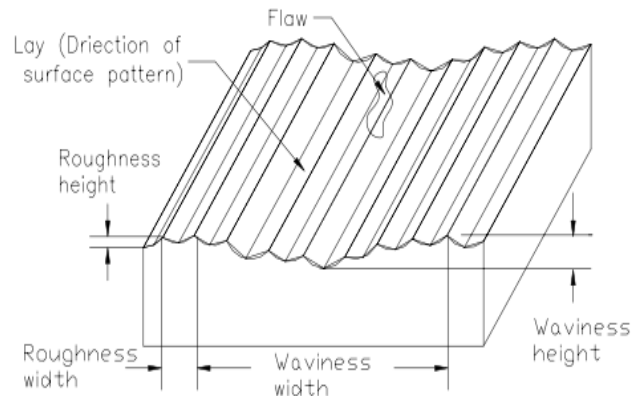


**Figure 2-3: Surface quality explanation**  
(Mike, *et al.*, 1998-1999).

Surface roughness is represented by the degree of smoothness of a particular surface. The quantitative measurements of surface quality in metal surfaces are a well-established standard. For composite Class A finishing these measurement standards are, however, less clear although a standard is in the process of being formulated (Raja, 2005; Debolt, 2004).

For purposes of the current study, the surface roughness will serve as a quality measurement and the knowledge already available from the metal industry will be sufficient. Surface roughness has different parameters, and therefore choosing the correct one to measure is important.

## 2.2.1 SURFACE ROUGHNESS PARAMETERS

The basic parameters of surface textures are  $R_a$ ,  $R_q$ ,  $R_z$ ,  $R_{max}$ ,  $R_p$ ,  $R_{pm}$ ,  $R_v$ ,  $R_t$ ,  $W_t$ .  $R_a$ , which is the arithmetic average of the absolute values of the roughness profile ordinates, is the most commonly specified parameter. Figure 2-4 illustrates the  $R_a$ ,  $R_z$  and  $R_{max}$  parameters (MacKenzie, 2008).

The  $R_a$  value alone cannot be an indicator of the surface roughness because different surfaces can have the same  $R_a$ . And thus, the  $R_z$  value is usually implemented together with  $R_a$ .

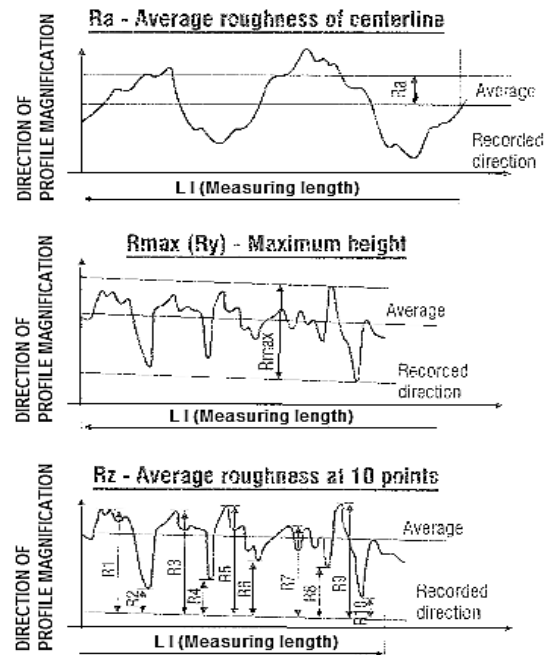


**Figure 2-4: Comparison between  $R_a$  vs.  $R_z$  and  $R_{max}(R_y)$ .**

However, for the purpose of this study the  $R_a$  value, as illustrated in Figure 2-4, is regarded as sufficiently accurate for indicating surface roughness, since the surfaces measured are flat surfaces. Various techniques and equipment are available for measuring these quality parameters of a surface (MacKenzie, 2008; Rapp, 2002).

## 2.2.2 MEASURING OF SURFACE ROUGHNESS

The techniques that are available to quantify the quality or roughness of a surface mentioned above can be divided into contact and non-contact techniques. Contact techniques can further be ranked into classes depending on the type of measurement used, namely stylus, optical or scanning methods. Stylus instrumentation is further divided into inductive methods and laser methods. These classes are illustrated in the diagram shown in Figure 2-5 (Sutherland, 2009).

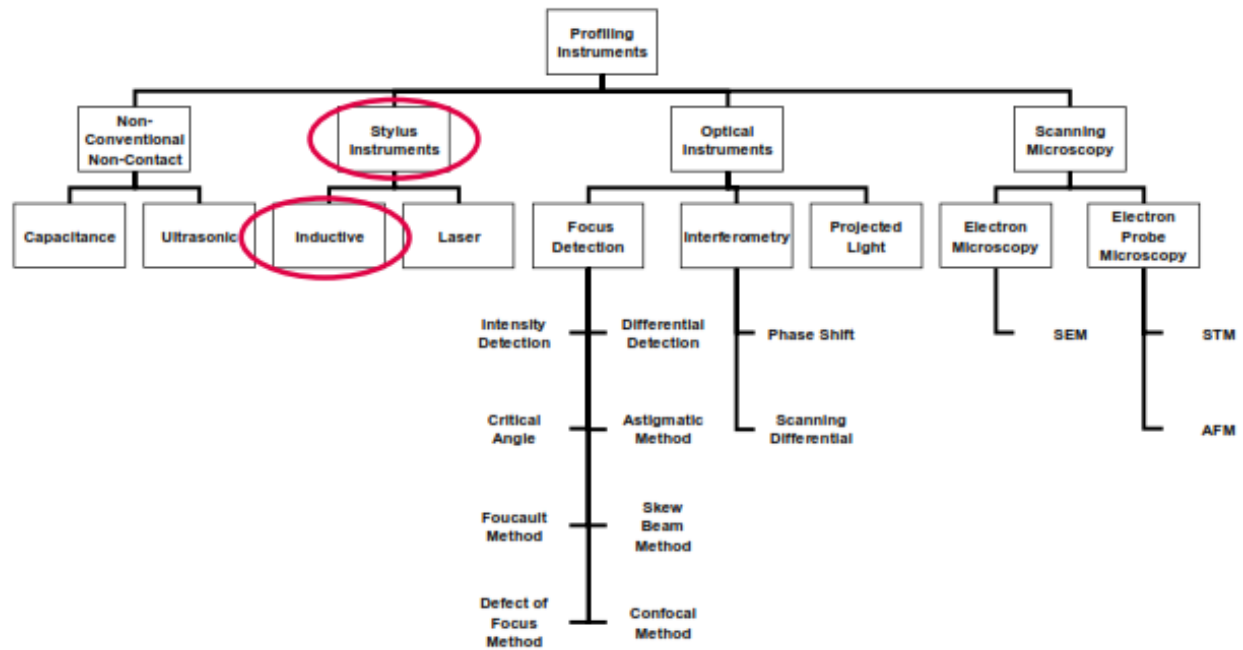


Figure 2-5: Types of profiling measuring methods (MacKenzie, 2008).

Direct measuring techniques would be more applicable for composite structures – and, since this study focuses on parts in a production cycle, stylus type instruments are more suitable. Because laser is usually used for metal-based materials, the more pliable choice for composite materials would thus be inductive stylus measuring devices.

The inductive stylus measurement uses a stylus that is drawn along the surface while registering a perpendicular motion of the stylus. The registered profile obtained is then used to calculate the roughness parameters (Sutherland, 2009). The device which uses this technique is called a profilometer.

Figure 2-6 shows a profilometer that uses a conical diamond stylus to measure the roughness. The resultant profile traces are also shown for a measurement perpendicular to the “lay”. To separate the surface wavelengths, a filter is applied to the profile data to transform the profile on the wave to a straight line.

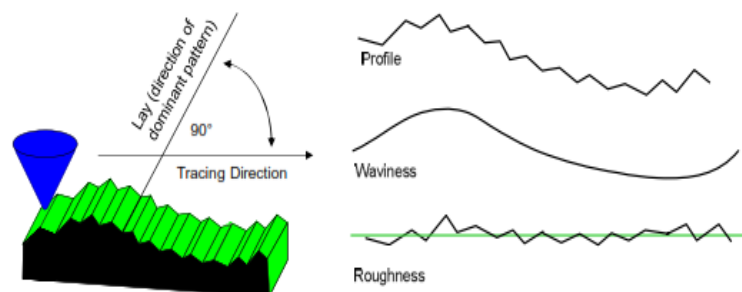


Figure 2-6: Waviness of a profile accounted for in the roughness (MacKenzie, 2008).

The length of the path that the skid traces is called the measurement length. Using the profilometer wrongly can lead to wrong measurements. A few guidelines for correct measurement techniques are provided in Appendix B (Degarmo *et al.*, 2003).

The surface roughness of the Class A finished parts used in this study will thus be measured with a profilometer. The next issues that need to be addressed are what the part comprises of, and how this composition can affect the surface roughness of the part.

### 2.3 INFLUENCES OF COMPOSITE LAYUPS ON FINISHING

A finished composite component or mould normally consists of two distinct components. These are the surface layers (which give the component its finish) and the structural substrate (which gives the component its strength and stiffness), as shown in Figure 2-7. In this study, the emphasis is on the finish layer and the main concern is how to achieve a Class A finish. However, effect of the substrate on the finish also needs to be considered.

As most moulds and components used at JS are manufactured from composite materials, the effect of these materials and the method of production on the surface finish will be investigated in this section. This study will consider composites as a mixture consisting of a



Figure 2-7: Composite surface layers (TIA, 2012).

polymer matrix with some sort of reinforcing fibre, in the form of laminates. These laminates are widely known as “FRP” – fibre-reinforced plastics (Wanberg, 2009).

### 2.3.1 COMPOSITE LAMINATE (FRP)

Continuous-fibre composites are materials that are laminated, as illustrated in Figure 2-8. These laminates are individual layers (or plies or laminas), which are orientated in directions that enhance the strength in the primary load direction (Campbell, 2004), as illustrated in Figure 2-8 (Pandey, 2004)..

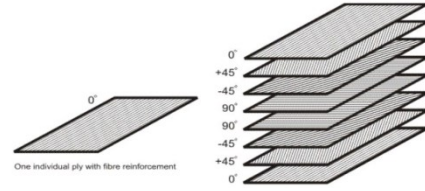


**Figure 2-8: stacking of composite laminates in directions (Pandey, 2004).**

$$\begin{Bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{Bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{16} & b_{11} & b_{12} & b_{16} \\ a_{21} & a_{22} & a_{26} & b_{21} & b_{22} & b_{26} \\ a_{61} & a_{62} & a_{66} & b_{61} & b_{62} & b_{66} \\ b_{11} & b_{12} & b_{16} & d_{11} & d_{12} & d_{16} \\ b_{21} & b_{22} & b_{26} & d_{21} & d_{22} & d_{26} \\ b_{61} & b_{62} & b_{66} & d_{61} & d_{62} & d_{66} \end{bmatrix} \begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \epsilon_{xy} \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix}$$

**Figure 2-9: Composite laminate ABD Matrix (Jonker, 2003).**

Because laminates are comprised of a few layers of individual materials, a theoretical matrix model exists to describe the different properties of a layup. This matrix is called the ABD matrix, and is predicated on presenting a relationship between the resultants of the forces and moments of a laminate to the strain in the laminate, as illustrated in Figure 2-9.

Each one of these elements represents a certain condition, or coupling between conditions, of the laminate's deformation. This is illustrated in Figure 2-10. By arranging the stacking order of the plies, one can eliminate certain deformation conditions in a laminate (Jonker, 2003).

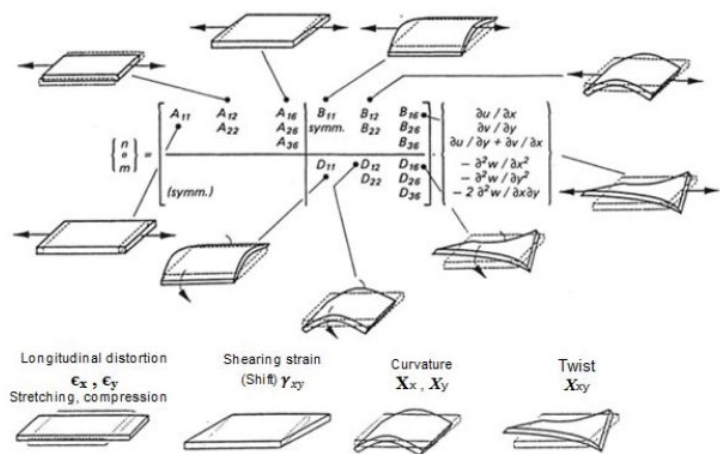


**Figure 2-10: Deformations of the composite laminate ABD matrix (Jonker, 2003).**

A number of these special laminating stacking orders to consider are the symmetric laminate, the balanced laminate and the quasi-isotropic laminate (Jonker, 2003). These three laminates can be explained as:

- ♦ **SYMMETRIC LAYUP:** A symmetric layup is a layup which is symmetric around the mid plane. The benefit of this layup is that it renders the B matrix zero and thus it

prevents coupling between the extension strains and the bending strains. This could be desirable in a mould layup, because such a situation can prevent the mould from bending and twisting.

- ◆ **BALANCED LAYUP:** In a balanced layup, the number of plies in any given direction is the same. This results in the  $A_{16}$  and  $A_{26}$  elements being zero and thus preventing the coupling of the in-plane extension and shear responses.
- ◆ **QUASI-ISOTROPIC LAYUP:** This layup simulates a normal isotropic material behaviour, which has the same properties in all directions. It can be obtained by either one of  $(0,45-45,90)_s$  or  $(0,60,-60)_s$  layup schedule. This laminate is beneficial where clear knowledge of the loading conditions of a laminate is lacking.

All three of these layup conditions could be beneficial to mould layups since one would like to prevent any twisting and bending, extension in the in-plane and shear, and the true loading conditions is unknown, due to unknown clamping and demoulding forces. This study will thus make use of a combination of these three layup schedules in order to obtain a good layup schedule for moulds. Another consideration with the layup of the lamina is how the lamina intersect with each other.

### 2.3.2 INTERSECTION OF LAMINATE LAYERS

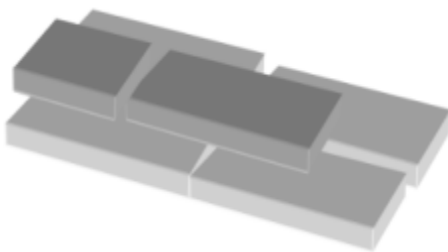


**Figure 2-11: Butt and brick layup of composite laminates**

When laying up a composite lamina, one can either have one long uncut lamina or one could use smaller pieces. The use of smaller pieces helps to reduce the pre-induced stresses caused by long fibres, and it also adds strength to joining lines (TIA 5, 2012). With the use of smaller pieces, the layers can be butt layup up and overlapping layers can be positioned in a brick-overlap style, as illustrated in Figure 2-11.

This method will be used in this study for mould layups to release the pre-induced stresses normally associated with long large moulds.

The materials used in FRP are as important as the order in which those materials are used. These materials, which entail the polymer matrix and some sort of reinforcing fibre, can have significant impacts on the final composite structure.

### 2.3.3 COMPOSITE MATERIAL CONSIDERATIONS

Because the composition of the composite parts in this study has already been determined, the survey will not consider the influence of materials of the part on the finish; however, the mould is also a composite structure, the attributes of which are undetermined. This section thus considered the influences of the material selection of moulds on the surface quality of the mould.

Moulds can be manufactured from a wide variety of materials. These materials vary from simple wooden mould to moulds made from compressed wood, to specialised tooling boards, and finally, composite materials referred to as fibre-reinforced plastic (FRP). Each of these materials has its own advantages and disadvantages. FRP is best suitable for moulds with a planar and compound curved surface. If a long tool life is required, the correct selection of resins and fibre can ensure this (Wanberg, 2009).

There is a wide variety of fibre and resins that are suitable for mould manufacture. The selection can be simplified when the different properties of these materials are compared. Table 2-2 gives the basic properties of three types of resins.

*Table 2-2: Comparison of the main types of resin (Wanberg, 2009)*

|                                  | COST             | MECHANICAL<br>& THERMAL<br>PROPERTIES | CURING<br>TIME                         | VOC* | CURE<br>SHRINK<br>AGE | BEST USED FOR...                                        |
|----------------------------------|------------------|---------------------------------------|----------------------------------------|------|-----------------------|---------------------------------------------------------|
| <b>POLYESTER<br/>RESIN</b>       | Low              | Low                                   | Moderate to<br>fast (limited<br>range) | High | High                  | General purpose, low-<br>performance, non-<br>critical  |
| <b>VINYL<br/>ESTER<br/>RESIN</b> | Moderate         | Moderate                              | Moderate to<br>fast (limited<br>range) | High | High                  | Special purpose, good<br>performance, non-<br>critical  |
| <b>EPOXY<br/>RESIN</b>           | Moderate to high | High                                  | Slow to fast                           | Low  | Low                   | High performance and<br>safety-critical<br>applications |

\* VOC- Volatile Organic Compounds

The three main types of resins on the market are polyester resin, vinyl ester resin and epoxy resin. Table 2-2 shows that although epoxy resin is more expensive, it also has low curing shrinkage and very good mechanical and thermal properties. It is used for high-performance and safety critical applications.

Although moulds do not present significant safety critical aspects, a mould does require low shrinkage as the part should not be smaller than it was designed to be. Figure 2-12 also shows that epoxy resins have, on average, a higher tensile strength and stiffness. Due to this attribute, this study will make use of epoxy

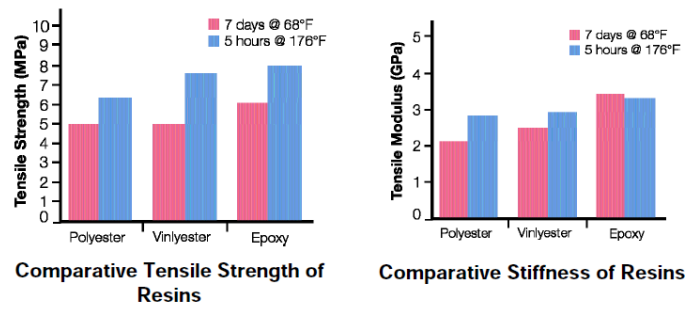


**Figure 2-12: Comparison of resin type strengths (SP Systems, 2013)**

resins and gelcoats, because the moulds will be subjected to production rates which will require these increased mechanical properties as well as low shrinkage rates (Wanberg, 2009).

The most common fibre types, E-glass, S-Glass, Carbon, Aramid and Hybrid are compared in Table 2-3 (Wanberg, 2009).

**Table 2-3: Comparison of the most common reinforcement types (Wanberg, 2009)**

|                | COST            | WEIGHT   | LAMINATE REGIDITY | LAMINATE IMPACT STRENGTH | BEST USED FOR                                        |
|----------------|-----------------|----------|-------------------|--------------------------|------------------------------------------------------|
| <b>E-GLASS</b> | Low             | Heavy    | Flexible          | Good                     | General purpose, non-critical parts and structures   |
| <b>S-GLASS</b> | Low to Moderate | Heavy    | Flexible          | Excellent                | Special purpose, good performance structural uses    |
| <b>CARBON</b>  | High            | Light    | Stiff             | Poor                     | High-performance high-stiffness structures           |
| <b>ARAMID</b>  | Moderate        | Moderate | Flexible          | Excellent                | High strength ballistics/abrasion and safety uses    |
| <b>HYBRID</b>  | Moderate        | Moderate | Flexible to stiff | Good                     | Special purpose, good performance and aesthetic uses |

The most popular material used for composite mould-making is fibre glass due to its low cost and availability. Fibre glass itself has various types, with the most common being E-glass and S-glass. E-glass is economical and electrical grade and S-glass is a high performance with about 25% more strength than E-glass. This study will make use of S-glass or E-glass, as the cost is low and it is the fairly general choice for mould-making purposes (Wanberg, 2009).

Reinforcements also have different woven types, which in themselves present a number of aspects to consider. Common woven fabric types include plain weave, twill weave, satin

weave, basket weave, mat, veil, and unidirectional. A few of these are compared in Table 2-4.

**Table 2-4: Comparison of various weaves of reinforcements (Wanberg, 2009)**

|                     | Weave Stability | Wet-out   | Drape     | Best used for...                               |
|---------------------|-----------------|-----------|-----------|------------------------------------------------|
| <b>Plain weave</b>  | Excellent       | Good      | Poor      | High-performance, flat or low curvature shapes |
| <b>Twill weave</b>  | Good            | Good      | Good      | Good performance medium curvature shapes       |
| <b>Satin weave</b>  | Poor            | Poor      | Excellent | General purpose high curvature shapes          |
| <b>Basket weave</b> | Good            | Excellent | Poor      | Good-performance flat or low curvature shapes  |

It can be seen from Table 2-4 that each of the weave types has certain applications where it would be most suitable. Choosing the best woven material for moulds thus depends on the application. For example, if the mould has parts which are fairly intricate, it would better to choose a satin weave than a plain or basket weave. If one only wants to build up the bulk of mould, then basket weave would probably work better than satin weave. Thus, it is necessary to have a sound understanding of the types of weave and their advantages and disadvantages so that one can apply this knowledge to the application at hand. Woven materials, however, are not the only type of fibre to consider, and mat and veil are both widely used in the mould-making industry.

Mat is used for its multi-directional strength and for quick build-up of laminates. Although mat has good multi-directional strength, it has large gaps between the fibres. This attribute may cause the fibre to harbour excess resin, resulting in a heavy and brittle composite. Although mat is widely used for mould-making, this study will rather make use of the woven fabrics for mould laminates, also because of their availability at the factory (Wanberg, 2009).

Veil is a very thin cobweb-like mat and can be used as a print barrier. Print barriers are used to prevent the print-through of underlying layers. Print-through occurs when a laminate is heated and cooled, and the fibres and resin within the laminate expand and contract slightly. This process results in a faint image of the fibre weaves in the surface of the laminate. Veil is then placed between the surface and the structural layers to prevent the print-through. Because the veil fibre is orientated in all the directions and also because it is thinner than the other materials, it will fill and bridge the print through gaps created. This material requires further investigation to determine how many layers are necessary to bridge the print-through (Wanberg, 2009).

This study will make use of a composite constructed of epoxy resins, woven glass fibres and possibly veil. Because the use of print barriers is a fairly new application, this area will require further investigation. Related to considerations regarding the type of materials used, is the issue of how to strengthen the more intricate parts of moulds such as female radii and sharp corners.

### 2.3.4 LAYUP CONSIDERATIONS

Components with sharp corners should, as a general rule, be avoided in the context of manufacturing from composite materials. This is mainly because laminates tend to bridge sharp corners and trap air bubbles in these corners. Tooling is therefore normally designed with smooth edges and fillets in corners. However, sharp corners are sometimes unavoidable.

Tooling tends to have sharp corners in the areas where two female moulds come together to form the split lines, called the intersection corners. This sharp split line is usually created by the plug, and is unavoidable when manufacturing the mould.

Strengthening these corners is necessary as the corners make up the area mostly introduced to trim or demoulding tools. This area can be strengthened by various means.

One method is to press glass rovings, mixed with resin, into the female corners or smaller radii, as illustrated in Figure 2-13. The corner is strengthened by ensuring more fibres and less resin in the corners (TIA 5, 2012).

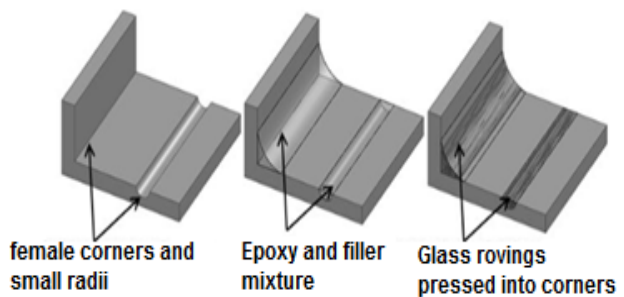


**Figure 2-13: Strengthening of female radii**  
(TIA 5, 2012).

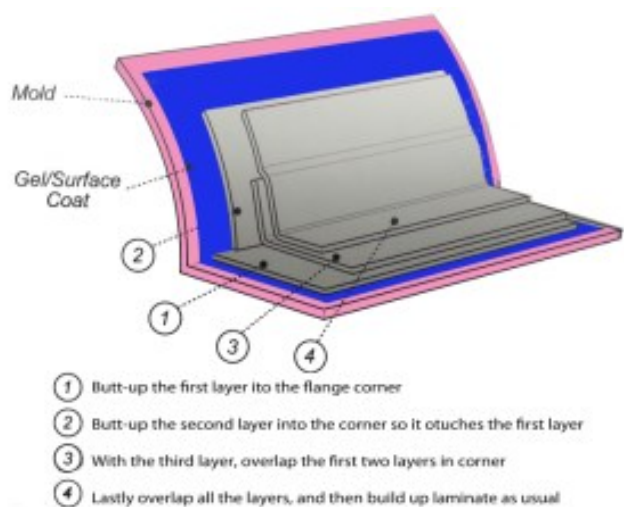


**Figure 2-14: Strengthening of female corners**  
(Wanberg, 2012).

Butting up the corners, as illustrated in Figure 2-14, is another widely used method. Strengthening female corners will, however, require more experimentation as general agreement as to the best strengthening method has not yet been reached (Wanberg, 2012).

## 2.4 PLUG FINISHING CONSIDERATIONS

A plug consists mainly of the component profile of the part and a split surface. The plug surface layers and their finishing are among the most critical elements of the plug. These finishings can be divided into the profile finish, the split surface finish and the intersection of the profile and split surface finish, as illustrated in Figure 2-15 (Wanberg, 2012).

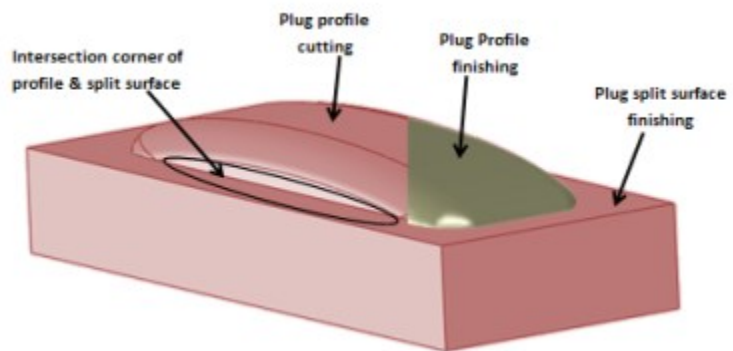


*Figure 2-15: Finishing areas of the plug*

The plugs considered in this study consist of two layers, namely the tooling board layer and the surface layers.

### 2.4.1 CAM MANUFACTURING

To manufacture precise CAD models for plugs is fairly difficult by hand, if not impossible, even for expert craftsmen. CNC or CAM manufacturing software overcame this stumbling block by performing the necessary calculations to obtain the contours directly from the designed CAD model. The computerised combination of design and manufacturing allows for a unified, combined process. This means that even a fairly unskilled operator can manufacture a very complicated plug or tool (Morena, 1994).

The main challenges of modern machining are how to achieve high quality in terms of the part dimension accuracy, surface finish, less wear on cutting tools and high production rates. It is thus very important to control the process in order to achieve a better quality in the final product (Rashid & Abdul Lani, 2010).

The CNC milling process mechanisms for forming the surface roughness is a very difficult and dynamic process, and depend on the specific process one uses. Various factors influence the final surface roughness. Some of these factors are controllable, such as the spindle feed, the feed rate and the depth of the cut; but some are uncontrollable – these include the tool geometry and the material property compatibility of the work piece and the tool. These factors can be determined by either using trial and error methods or by means of multiple regression methods (Rashid & Abdul Lani, 2010; Mike *et al.*, 1998-1999).

These methods, however, are better suited for machining parts that differ vastly in dimensions and materials, making it very difficult to predict similar surface roughness. This project, on the other hand, focuses on one material, namely Nucoron651, and the plug contours are for the most part on the same level of intricacy. The only factors needing prediction here are the spindle feed, the feed rate and the depth of cut. The following section will briefly explain these factors and their importance, and also indicate how they can be easily calculated by means of a trial and error method (Julie *et al.*, 2006).

#### 2.4.1.1 EFFECT OF STEPOVER

The tool path of CNC is a concept that is based on one tool path being an offset from another tool path. This offset is called the step-over. CAM software usually includes various tool path styles, of which the most common are the raster (sometimes called a zigzag) and the contour offset, as illustrated in Figure 2-16. The user choses the step-over value which is adjacent sections of these tool paths (CNC cookbook, n.d.).



Figure 2-16: (Left) Contour offset. (Right) raster offset (CNC cookbook, n.d.)

Figure 2-16 shows the arrangement of the tool paths from the top view. However, to understand the influence on the surface finish, one needs to look at the side view, which is called scalloping, as illustrated in Figure 2-17.

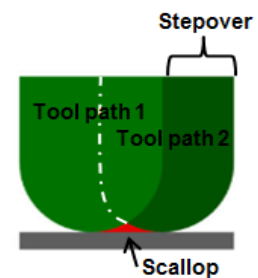


Figure 2-17: Scalloping (CNC cookbook, n.d.).

This red area is the leftover of the material on the part between the tool path offsets. These are not really shown in the CAD environment and will only be noticeable after cutting, which means that the wrong choice here can have a significant influence on the surface

roughness. These leftovers will have to be removed after machining by means of sanding and polishing (CNC cookbook, n.d.). This task can greatly influence the time it takes to finish a cut plug by days, but again – if chosen correctly, it can also greatly reduce the plug creation time and result in quicker, more accurate plugs. These plugs will create good mould surfaces and ultimately result in Class A finished parts. Figure 2-16 illustrates the importance of the step-over by showing step-over influences of various sizes of tools.

In light of what is shown in Figure 2-17, it can be said that the scallop height and the step-over mutually increase the value of one another, as illustrated in Figure 2-18. Thus a higher step-over will result in a higher scallop; Figure 2-18 illustrate a step-over equal to 1/10, 1/5 and 1/3 of the tool diameter and show the resultant scallop (or rather surface roughness).

The change in the quality is thus so dramatic that one might be tempted to always use the smallest step-over possible. Using a small step-over is good, but the compromise is time. The time is increased because the total length of a tool path will roughly double if the step-over is cut in half (CNC cookbook, n.d.).

There is a point where the time and quality can both be of the utmost importance, a situation that is illustrated in Figure 2-19. Here, as an example, is a situation that is normalised to a tool diameter of 1.0 mm, for ease of scaling it to any other tool diameter.

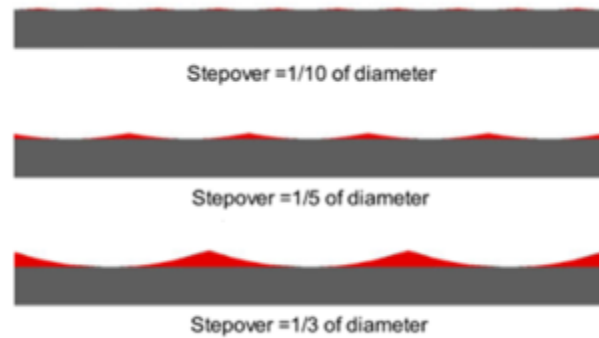


**Figure 2-18: Scalping as the result of different stepover chosen (CNC cookbook, n.d.)**

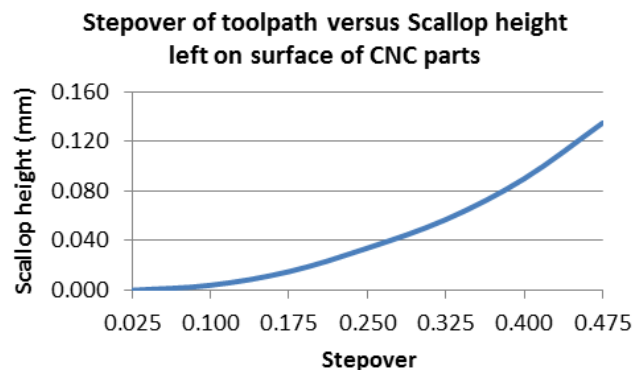


**Figure 2-19: Stepover of tool path versus scallop height (CNC cookbook, n.d.).**

To further elaborate on the tool above, it can be said that for a given step-over chosen, a larger tool diameter can result in a slightly smaller scallop. This results in a better quality surface finish if the same step-over is chosen for larger tools than for smaller tools, as illustrated in Figure 2-20.

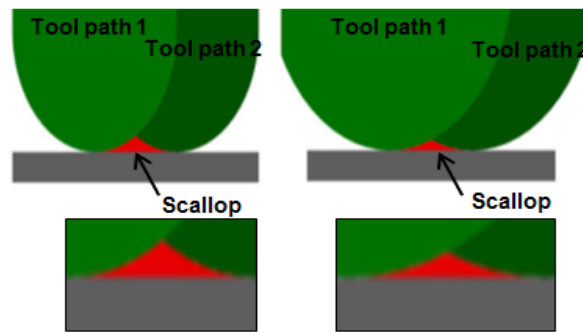


**Figure 2-20: Scallop of a small tool versus a larger tool**  
(CNC cookbook, n.d.)

The step-over should be chosen according to the material being used and in accordance with the resources. If the material is rather soft, it might be better to first achieve a rougher finish and then sand afterwards. This is because the machine might require an hour longer for cutting, whilst a person might have sanded to achieve the same finish in 10 minutes (CNC cookbook, n.d.).

This project is, however, only interested in one material, namely Nuceron651, which is a hard tooling board. Hard tooling board can be challenging to sand by hand and it may be worth doubling the machining time to obtain a better finish. To summarise how to choose a step-over towards obtaining the best surface finish, there are a few rules of thumb that are highly recommended (CNC cookbook, n.d.):

- ◆ The step-over should be between  $1/3$  and  $1/10$  of the tool diameter.
- ◆ For soft materials, a larger step-over of between  $1/5$  and  $1/3$  in range can be used.
- ◆ For harder materials, a smaller step-over of between  $1/5$  to  $1/10$  in range can be used.
- ◆ The largest tool possible for the machine geometry should be chosen.

After the step-over has been selected, the other two significant parameters are the feed and speed.

#### 2.4.1.2 EFFECT OF FEEDS AND SPEEDS

The basic terms that one should consider in the context of CNC are speeds and feeds. The spindle speed of the machine in rpm (revolutions per minute) is referred to as the speed. The spindle speed is considered to be the most significant determiner of the life of the machine's tools. If a machine runs too fast, excess heat is generated which causes the tool to soften, which results in a dulling of the edges (CNC cookbook, n.d.)

Feeds, in turn, refer to the rate at which feed is provided and is given in a linear unit per minute (inches or mm per minute). The feed is, essentially the maximising of the material removal rate.

There is what is referred to as a 'sweet spot' for every cutting operation. It is point that has to be hit exactly, but if it is missed, it may not make a very significant difference. Once the sweet spot is known, the machine parameters can be tweaked in order to maximise the removal rates, to ensure that tools remain sufficiently sharp and that the surface finish is the best quality possible (CNC cookbook, n.d.).

Slowing down the speed rate to slightly less than the appropriate maximum provides the best tool life, but it also results in longer cutting time. By reducing the feed rate whilst keeping the spindle speed up lightens the material removal and leads to a better surface finish (CNC cookbook, n.d.). There is, nonetheless, a limit where the feed rate is too fast – and this may cause the tools to start rubbing; tool life will also be reduced due to the excess heat generated by the rubbing. Feeding too slowly also leads to rubbing instead of cutting, which of course also reduces the tool's life.

Two further guidelines to follow, other than the optimum feed, speed and step-over, in order to achieve a good surface finish with CNC machining are (CNC cookbook, n.d.):

◆ **Use different tools for roughing and finishing**

It is good practice to switch tools between the roughing process and the finishing process. The brand new sharp tools should be used for finishing and these tools could then be rotated to roughing work once they have become blunt.

◆ **Reducing the depth of cut for finish pass**

The depth of cut should be reduced when cutting the finish compared to the roughing by a few thousandths, which will result in only using the side and not the bottom of the cutter, which yields a better surface finish.

As the material used for this project will be confined to Nucron651, the ultimate feed and speed ratios can easily be determined by the trial and error method. Specifically, this is achieved by creating a matrix of various feeds, speeds and step-over and then measuring the final results with a profilometer.

### 2.4.1.3 SOFTWARE INFLUENCES OF CAD AND CAM ON CNC SURFACE FINISHES

The correct step-over, speeds and feeds are definitely the correct parameters to optimise, but these are not the only variables that have a bearing on a good surface finish. A great many of the quality aspects of a finished cut are influenced by the CAD/CAM software used to create the part program. For a good example Figure 2-21 shows parts which exhibit a faceted surface finish, which was caused by the software used. This section will discuss some of these critical software influences (CNC cookbook, n.d.):



**Figure 2-21: Faceted surfaces due to the software influences (CNC cookbook, n.d.)**

#### ◆ Chordal tolerances

CAD and CAM programs simulate smooth flowing curves by means of a series of small line segments, as illustrated Figure 2-22. The chordal tolerance is defined as the circle is created by lines on the chord. If a chordal tolerance that is too low is chosen, one might end up with a faceted finish like the part described earlier. For mould or plug surfaces, the tolerances might be chosen as low as 0.00004 inches (0.04 mm) to achieve a sufficiently good surface finish (CNC cookbook, n.d.).

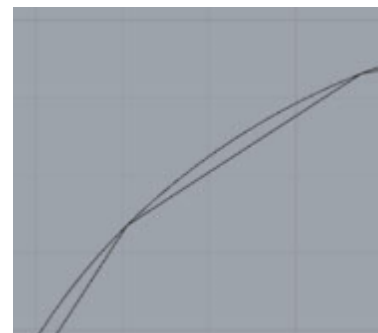


**Figure 2-22: Simulated curve as a series of line segments (CNC cookbook, n.d.)**

#### ◆ CAD file format issues

A parameter which is related to chordal tolerances is the file format. The CAD and CAM programs tolerances for the matching file format, like an STL file, must be set to the same sufficiently small tolerances to avoid visible faceting (CNC cookbook, n.d.).

#### ◆ Climb versus conventional milling

Most CNC machinists are taught to always use climb milling, although conventional milling might sometimes yield better results. The difference between these two different methods is that climb milling requires less cutting force, which is one argument for always using it; however, climb milling deflects into the wall of the cut

in comparison to conventional milling which instead deflects along the path. When one looks at a part along a very oblique angle, minute variations can be seen which are due to the cutter which deflected into the wall, thus creating a wavy effect. This is why conventional cutting might produce higher quality surfaces in some selected cases. To overcome this obstacle, it is suggested that the finishing cuts should be conventional rather than climb; however, one might have to experiment with both to obtain the best results if surface finish quality is an absolute must (CNC cookbook, n.d.).

◆ **Tactical tool path considerations: entries, exits, corners and dwells**

Any change in a tool path is an opportunity for a surface finish problem. These changes occur when the material is entered or left, when there is a change in direction from a straight line or smooth arc, or when the tool stops moving (CNC cookbook, n.d.).

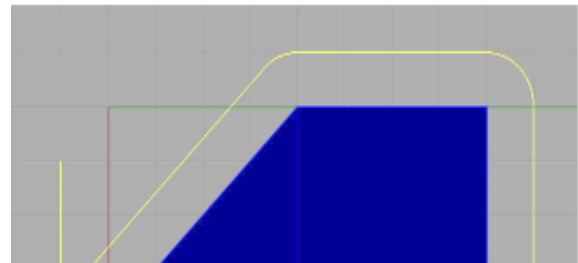


*Figure 2-23: Tangential entry and exits creating smooth tool paths (CNC cookbook, n.d.)*

Each of these individual changes can disturb the cutter in such a way as to leave a mark in the surface finish. The CAD and CAM operators should do their utmost to minimise these changes as to the great benefit of improved surface qualities. For instance, sharp corners can be blended by putting arcs on corners or fillets on sharp edges. The same should be done for entering or exiting a profile. The tool should be perpendicularly aligned to the wall when attempting and make the move tangential. By aligning the entry and exit tangentially on corners, the ideal entry and exit points can be obtained, as illustrated in Figure 2-23 (CNC cookbook, n.d.).

This section concludes by noting that the optimum combination of step over, feeds, speeds, tools and CAD and CAM practices should be chosen to obtain the best surface finish from CNC cutting. However, with all these methods, the surface of a plug or tool will still require some sanding and paint spraying to ensure that the surface is as smooth as possible. These finishing processes will be discussed in the following section.

## 2.4.2 PLUG SURFACE LAYERS

The plug surface finish can be created by means of conventional methods like spraying and sanding the plug or by non-conventional methods whereby special types of stand-alone materials are added to the surface.

Plug surfaces are typically only used once or twice to create the moulds. This results in the materials of plugs having the best possible quality surface finish, but they may have low scratch and durability resistances. The surface layers of plugs can be divided into the materials needed for the flanges, and the materials needed for the plug profile, as illustrated in Figure 2-24.

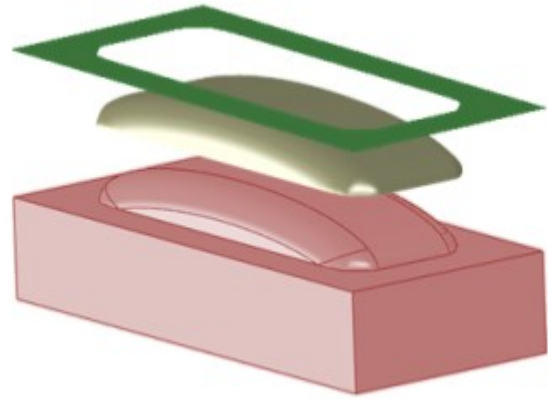


*Figure 2-24: Plug with materials added for split surface and profile*

Flanges need to be made of smooth materials, especially in the case of parts which may require vacuum bagging. This is because as vacuum bagging requires smooth areas for the sealing of the bags. Materials that are generally smooth and that work well for plug flange include acrylic, styrene, polypropylene or wood sheets (Masonite or MDF). The flange is usually flat and the materials could thus include hard sheets like acrylic sheets. For the more intricate profiles, automotive wrapping materials can be considered. These materials will now be discussed (Wanberg, 2012).

### 2.4.2.1 WRAPPING MATERIALS

Automotive wrapping materials can be divided into paint protection films (PPF) and advertising wrapping film. PPF films are usually constructed of polyurethane and advertising wrapping film is usually made of vinyl. The main difference between polyurethane and vinyl is that polyurethane has no plasticisers which can leak out and cause embrittlement over time. The result is that a polyurethane film will retain its flexibility and shelf life over longer terms than vinyl sheets. This quality also makes polyurethane sheets easier to apply than vinyl sheets especially over contours (Argotec, 2008-2013).

PPF films have become necessary in the automotive finishing sector due to modern water-based paints no longer having the resilience of older solvent-based paints (Paint Shield, n.d.).

The product is a composition of a release liner, an acrylic adhesive layer, a polyurethane film, a PUR clear coat and an optional pre-mask, as illustrated in Figure 2-25. The release liner ensures that the film can easily be removed, if needed, whilst the adhesion layer makes it adhere to the underlying surface. The polyurethane film provides the actual protection and the clear coat is an added protection layer to the polyurethane film; this helps with the initial clarity and weathering resistance (3M, 2011).

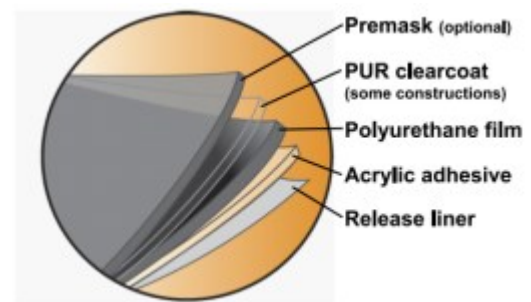


**Figure 2-25: 3M Scotchguard PPF construction (3M, 2011)**

These films have recently been introduced into the aviation industry. Vehicle Protection Shield is a company which applies PPF to a few leading edges on an aircraft, including the wings, tail plane, lift struts, landing gear cuffs and the wheel spats. From these applications, one can gather that it is possible to apply these films over the intricate contours of aircraft shapes (VPS, 2012).



**Figure 2-26: A car wrapped with an animal print vinyl next to the original car (Mjet, 2006).**

In the automotive industry, car wrapping for advertising or customising has become more widely used. This type of wrapping is usually achieved through vinyl wrapping. The vinyl easily conforms to contours and can be set into place if care is taken to do so. Figure 2-26 shows a car wrapped with a vinyl film next to a similar car with the original paint finish. Like PPF, vinyl also provides a measure of protection to the underlying paint. Vinyl thicknesses differ, but are on average about 90 microns thick (Berg, 2013; Mjet, 2006).

These materials neither have a known surface roughness, nor is it known how release agents and mould surface layers react to these materials. Experimentation is thus required to evaluate these materials as possible plug finishing materials.

#### 2.4.2.2 ACRYLIC SHEETS

Acrylic is a widely used material. It consists of a cell cast high molecular mass and comes in sheets (Perspex SA, n.d.). These sheets are available in a wide range of varying thicknesses, colours and even surface patterns. The surface finish of these sheets can also vary, depending on the manufacturer and type, but are generally acrylics have a high gloss, hard finish and can be compared to clear glass (Pilkington, 2009).

To maintain the good surface finish with which these sheets were manufactured, they are masked upon fabrication with self-adhesive polyethylene masking film (Perspex SA, n.d.). These films can be retained during any fabrication work and should only be removed as late in the process as possible. These protection films may help to ensure that the surface will not require cleansing until necessary; however in some cases cleansing might be required (Babin, n.d.).

Cleansing of this surface must only be done with clean cold water to which a little detergent has been added. The use of solvents like turpentine or spirits is neither needed nor recommended (Perspex SA, n.d.).

Acrylic sheets can be manufactured into various intricate-two dimensional shapes and can even be engraved if needed. This manufacturing can be done by machining, sawing, cutting or laser cutting. Acrylic sheets cut by laser can provide smooth edges and interior contours without any supplementary finishing. This project will make use of laser cutting for cutting acrylic sheets to conform to the split surfaces of the mould and to ensure that the intricate contours of the profile are adhered to (Trotec, n.d.).

Acrylic sheets are, furthermore, widely used as a plug split surface material (Wanberg, 2012). The current study will confirm this usability and measure the surface finish that it provides to the projected mould surface. After the plug has been finished, the mould construction can commence.

## 2.5 COMPOSITE TOOLING CONSIDERATIONS

Construction of composite moulds can be divided into the designing of the mould, the construction of the mould and obtaining the perfect mould surface finish. In section 2.3, the influences of the layups and materials of composite materials were discussed, and the applicability of various layups and materials for either the mould or part was discussed. This section focuses on influences on the mould design and construction.

### 2.5.1 DESIGN CONSIDERATIONS OF MOULDS AND PARTS

The surface finishing of a mould is not directly influenced by the dimensional design of the part, but poor part/mould designs can influence the demoulding capabilities. If a part demoulds with difficulty, the mould or part can be severely damaged and this damage can cause surface discrepancies. A few guidelines on the geometric designs of parts and moulds exist (Wanberg, 2012).

In Figure 2-27, few considerations of dimensional influences (with an indication of design quality) are provided (Wanberg, 2012). The illustration highlights the following factors:

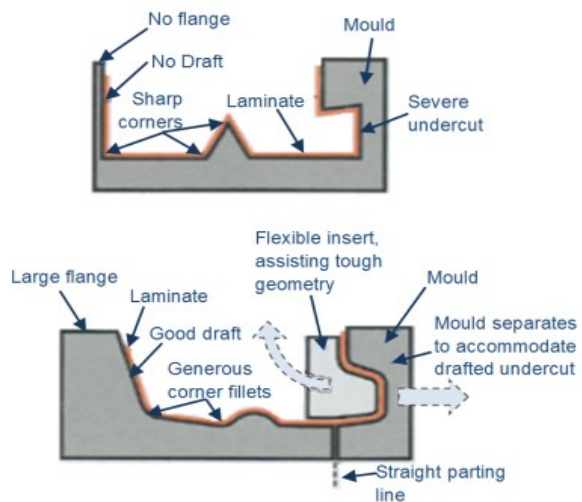


**Figure 2-27: Design considerations of moulds and parts. (Wanberg, 2012)**

- ◆ **FLANGES:** Large flanges provide stiffness necessary for moulding side walls and provide areas for mould inserts, like alignment pins, vacuum ports, demoulding assistance, trim plates, etc.
- ◆ **DRAFT ANGLES:** Proper draft angles help to release the part.
- ◆ **GENEROUS CORNER FILLETS:** Fillets on corners assist with layup on fibres, as fibres can more easily fill a filleted corner, than a sharp corner. Corner fillets also assist with demoulding.

- ◆ **PARTED MOULDS & INSERTS:** Moulds with intricate geometry can be parted into multiple moulds to help with demoulding of parts. Flexible inserts can be used to assist with shaping tough geometric shapes.

These are only a few mould design considerations; however the mould materials can also greatly influence the mould manufacturing and the lifetime of a mould.

## 2.5.2 MANUFACTURING OF COMPOSITE MOULDS

The moulding process is fairly unique for every part, material, and mould design used. This study will make use of composite moulds with a tooling gelcoat surface layer produced upon a plug (DME, n.d.).

Depending on the curing methods and materials of the composite part, the composite tool can either be classified as a low temperature tool or a high temperature tool. Low temperature tooling is tooling of which the part material is applied and then cures at room temperature. High temperature tooling is tooling which is normally associated with curing of parts well above room temperature and which usually requires autoclave or heating features in the mould (TIA 5, 2012).

This study will mostly focus on low temperature tooling, as parts in the JS factory cure at room temperature. The focus will be on the surface layers, as this influences the finishing, thus other tooling aspects are not covered by this study.

## 2.5.3 MOULD SURFACE LAYERS

A mould's surface must be as smooth as possible, both with a view to improve the demoulding of the cured part, and also to minimise the finishing of the parts after demoulding. Composite parts have thermoset resins which accurately reproduce textures from the mould surface onto the part surface on microscopic level. This extra detail and texture, if it contains pits and pores, can lock resin of the part inside, thus making it more difficult to release. It is thus paramount that the mould surface must be highly reflective and free of visible scratches, and of course polished to a Class A finish (Wanberg, 2012).

The use of tooling gelcoats helps one to observe imperfections in a mould surface after mould layup and demoulding. It is difficult to determine the locations of surface flaws in a clear resin composite due to the bubbles in the composite being visible through the surface. By contrast, the tooling gelcoats have opaque surfaces that are easily inspected and will reveal any waves, high spots or low spots (Wanberg, 2012).

Tooling gelcoats can be polyester- or epoxy-based. This project will make use of epoxy-based gelcoats, based on the reasons explained in section 2.3.3 for using epoxy laminating resins.

Applying tooling gelcoats can proceed in the form of spraying or brushing. Most professional mould makers prefer the spraying application, as they make use of polyester tooling gelcoats. Epoxy tooling gelcoats are quite hazardous and it is recommended to rather apply these with brushes (Wanberg, 2012; Morena, 1994).

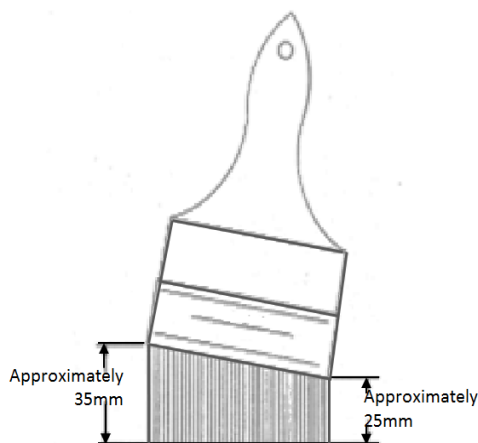


**Figure 2-28: Brush trimming for gelcoat application (Morena, 1994)**

A few guidelines are available for applying tooling gelcoat with a brush. The gelcoat must be applied with a brush, the hair of which must be trimmed shorter than normally to increase the stiffness of the brush, as illustrated in Figure 2-28. This helps to prevent air voids, as air is not trapped by lifting of the shorter brush air (Morena, 1994; Lion-Cachet, 2013)

The gelcoat must be applied in long even strokes (Fibreglass Warehouse, 2013). It is also suggested that two layers are applied, one on 0° and one on 90°. Heating the gelcoat whilst applying is also recommended in order to decrease the viscosity and increase the release of bubbles created on the surface (Clubkit clearcote, n.d.; Lion-Cachet, 2013).

For this project, the tooling gelcoat will be applied by means of a brush. This process will require more experimentation in order to ensure that the gelcoat is applied correctly and does not cause any unforeseen discrepancies after curing.

After the mould has been built, the first parts can be manufactured. In order to ensure that the first parts release from the moulds, a release agent is used. The release agent can influence the finishing layers of the part that is directly in contact with the release agent.

## 2.6 INFLUENCES OF RELEASE AGENTS ON SURFACE FINISHING

Release or demoulding agents are materials that have been specially formulated to prevent permanent bonding between the part and mould surface during part curing. These agents assist with the easy release of the manufactured part and could help with smoothing the moulded surface. Correct selection of the release agent can optimise the production time by improving consistency of surface finishes, minimising post mould operations and it could help to minimise fibre wet out (TIA 4, 2011). Figure 2-29 explains the necessity of a release system.

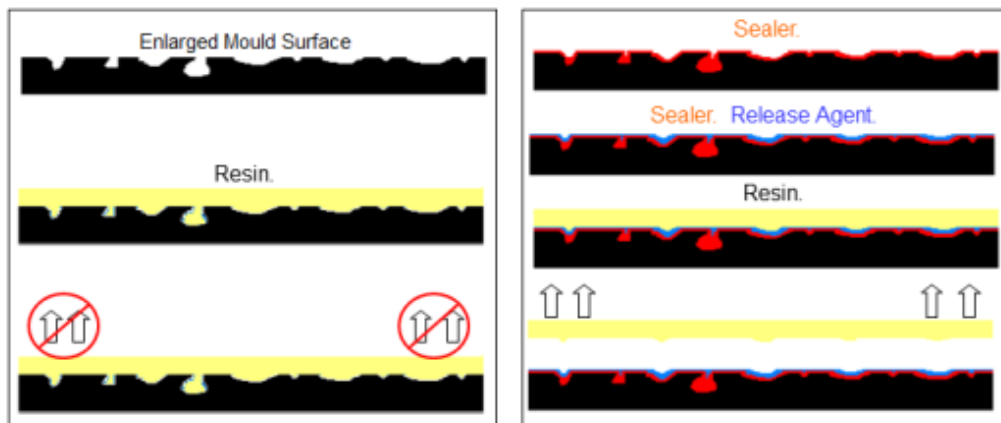


*Figure 2-29: Release agent necessity explained (Lion-Cachet, 2013).*

Release systems can be divided into external and internal release systems. Internal release systems form part of the mould surface when created. External release systems are applied afterwards. External release systems can be sub-categorised into waxes, PVA and semi-permanent release systems. Waxes and PVAs are usually incorporated with once-off or low production applications and semi-permanent systems with medium to high production cycles (TIA 4, 2011).

Choosing the correct semi-permanent release systems is important. There is no data available for these two systems, or for waxes, or for the applications of 2K paint; neither do we know how these react with certain automotive wrapping materials. These aspects will require more experimentation (Morena, 1994; Lion-Cachet, 2013).

## 2.7 CONCLUSION OF LITERATURE STUDY

It is concluded that Class A surface finishes are surfaces with extremely high quality that have been achieved by sanding them with a sanding grit higher than P800. Investigation into the exact grit sizes and surface roughnesses of Class A finishing for composites is required.

The following was concluded for the plug, mould and part surface finishing:

### **Plug surface finishing:**

It was found that a good plug surface can be obtained through the CNC machining process. The best speeds and feeds required for plug surfaces are not available from the literature and it was therefore decided to obtain these values experimentally as part of this investigation. The surface finishing of the plug could be done by either conventional or non-conventional methods. As the best method is not available, this aspect will also be investigated experimentally.

### **Mould surface finishing:**

It was clear that the mould surface required good finishing, which would allow for the part to demould easier and would also improve the part's finishing. Investigation of the usage of composite materials versus tooling board as mould materials was done by means of a survey on moulds in the JS factory.

When composite materials were used for mould manufacturing, the following was found: Epoxy resin is preferred over vinyl ester and polyester resins, due to its lower shrinkage and higher mechanical properties. Fibre glass is preferred over carbon fibre and aramid, due to its lower cost and availability. Twill and plain weaved fibres, with additional print barriers are preferred over chopped strand mat due to the better mechanical properties. Print through-prevention will require more experimentation.

Tooling gelcoat should be used for the surface finish. Brushing is preferred over spraying, but further investigation is required to ensure an efficient method. The mould not only requires a good surface finish, but must be strengthened in weaker areas such as female radii or sharp corners. This will be investigated through experimental methods.