Reverse Engineering of Obsolete Components for Realisation using Additive Manufacturing

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Abstract

Additive manufacturing (AM), or 3D printing as it also known, is a technique used for the direct manufacture of parts, one which is becoming more accessible to not just engineers in industry, but also non-technical users with minimal technical knowledge or experience.

The aim of the research was the investigation of the possibilities that AM presents for realising the manufacture of obsolete parts from older systems. Consideration of multiple AM techniques and their individual benefits and drawbacks is presented. To reverse engineer (RE) a part for additive manufacture requires the use of 3D modelling software packages as well as access to AM equipment to fully investigate how to best produce replacement parts. The thesis also considers various data creation and scanning technologies, used to digitise the geometry of parts, a key component in the RE process. The digitised component can then be manipulated in modelling software to provide the files required for AM.

To replace components from older systems that are no longer in production can incur massive costs with respect to their manufacture using various moulds, machinery and tools. Using AM, it is shown that these costs could be greatly reduced, and material waste kept to an absolute minimum. With the incorporation of 3D modelling and simulation/analysis software, the mechanical performance of a component is also analysed.

A component from an obsolete coffee roaster was subjected to the process of RE for replacement. The desktop AM machine used produced a part of sufficient quality to allow its use as a sandcasting pattern. By using AM instead of a traditional pattern, time savings and thus cost savings were achievable in the manufacturing process. A larger version of the component was scanned to create the 3D model from which the sandcasting pattern could be created. This was not successful as the 3D scanners could not produce a scan of satisfactory detail to work with. An investigation into the capabilities of the scanner was then carried out to determine if lower priced scanners are a worthwhile investment. This showed that while they are not ideal for 1:1 scaled replications of geometries, they are useful should a miniature version be required. It is recommended that scanners do not represent the same value for money in terms of quality produced that low end desktop AM machines do.

Disclaimer

Figures Included in this thesis are copyright of the author unless stated otherwise and have been produced during the course of this research. In the case of reference figures and images, reference has been made in the text where the figure is first described.

I hereby declare that this thesis is my own original work and has not previously been submitted for publication or for the award of any other degree.

Further, I have acknowledged all sources used and have cited these in the reference section.

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Glossary of Terms and Abbreviations

2D – Two-Dimensional

3D – Three-Dimensional

AM – Additive Manufacturing

CAE – Computer-Aided Engineering

CAM – Computer-Aided Manufacture

CNC – Computerised Numerical Control

DFM – Design for Manufacture

FDM – Fused Deposition Modelling

FEA – Finite Element Analysis

IR – Infrared

IRSL – Infrared Structured Light

RC – Rapid Casting

RE – Reverse Engineering

RP – Rapid Prototyping

SL – Stereolithography

SLS – Selective Laser Sintering

UV – Ultraviolet

1. Introduction

Additive manufacturing (AM) technologies have many uses in industrial sectors. Due to the unique layer-wise method of manufacturing components, it is very useful for the production of intricate and complex parts. It is ideal for complex shaped parts which would otherwise be difficult to produce using traditional manufacturing methods as parts are built up in a series of cross-sectional layers as opposed to being formed (e.g. moulded) or fabricated by subtractive methods (e.g. machined). An issue with industry as it stands now is that it is progressing with the manufacture of more and more new products all the time, so much so that older systems and their components are quickly becoming superseded and the manufacture of their parts is being halted. This presents a problem for both consumers and companies who rely on these older systems. Products or components become obsolete when they break down as it is no longer possible to purchase spare parts which are required for their continued operation. Therefore, this would incur an unnecessary loss of a system which would otherwise be a valid and functional asset, if a spare part or replacement component could be obtained. Whilst it is possible to have a part replaced using the original methods, the costs of machinery and tooling would far exceed any use that one component could yield, and so it would be an overly expensive investment. With the option of having a component manufactured using an AM method, the timescale and costs for realising the part is greatly reduced.

This thesis will explore the possibilities of using AM techniques to manufacture a replacement component of an obsolete product. It is not a new idea to use AM for the production of an end-use functional part, and the technology is often used in conjunction with traditional (more conventional) techniques. The focus of the work presented here will be to use a combination of traditional manufacturing methods and AM methods to reduce the costs of producing a parts as well as the added incentive of reducing the timescales required to produce the part. Further to this, the manufacturing options considered will incorporate low cost AM machines and processes. The processes used will be technologies which have an ease of use, such as plug-and-play desktop printers, therefore giving maximum accessibility.

Given that an obsolete component often does not come complete with a full set of drawings or 2D or 3D models, it is required to obtain this information by using the finished product and effectively working backwards to achieve the desired models and drawings to manufacture the part, this process is known as reverse engineering.

The requirement for AM is to have a ‘point cloud’ of data which makes up a 3D model. To obtain this model, a method of geometry collection must be used to convert the part from its physical state to a computer model. The geometry collection procedure can be done in multiple ways, as explored later in the thesis, however it forms a key step in reverse engineering a part.

A coffee roaster assembly was provided by J.Atkinsons & Co. which was in a non-operational state, presenting a system with missing parts ideal for a case study. The company uses older artisan machines to roast coffee in a traditional manner and the restoration of the small roaster would give the company an asset to use in small batch roasting, as well as a piece of operational roasting history.

An investigation was required after the case study on the quality of the scanners used for geometry collection, given the less than desirable results yielded upon reverse engineering the component for the coffee roaster. The aim was to determine if low budget scanner were capable of producing reasonable quality scans.

2. Reverse Engineering

When a part or product is manufactured using a conventional engineering process, data will accompany it. Depending on the complexity or intended use of the product, the documentation available can include a full set of drawings, analysis results, specifications and standards, materials, test results, as well as manufacture and assembly information etc. [1]. The method of duplicating an existing component, subassembly, or product, without the aid of documentation, drawings or computer models is known as reverse engineering [2]. Thus reverse engineering is the process of extracting information about the product from the product itself [3].

There are numerous applications of reverse engineering; it is often used in computing technologies for abstraction and redesign of software [4] as well as being used on electrical components. It is defined for use in this thesis however, to reverse engineer a mechanical component by analysing the existing objects physical dimensions, features, material and physical properties.

There are a number of reasons as to why one would reverse engineer a component or a subassembly:

1. The original manufacturer no longer makes a product.
2. The original manufacturer no longer exists, but a customer needs a replacement component.
3. The original supplier is unable or unwilling to provide additional parts.
4. There is insufficient documentation for the original design. Possibly it cannot be found or never existed.
5. There is existing documentation for a product, but components have been modified for use, thus existing documentation is no longer relevant.

6. To isolate the bad features and redesign an optimised product.
7. To improve upon good features of a product based on long-term usage.
8. To evaluate the good and bad features of competitors' product.
9. To understand competitor's products and develop superior products. [2]

2.1. Reverse Engineering Process

Reverse engineering an item does not follow a set procedure. There are a number of options to consider when recreating a component or system. In general though, the aim of reverse engineering is to create a three-dimensional (3D) geometric model from a physical object. This process is not the entirety of reverse engineering though it is a fundamental building block of the process as a whole [5]. Once the CAD model is obtained it can be used to directly manufacture the component or used to improve the design (Figure 2.1 [6]).

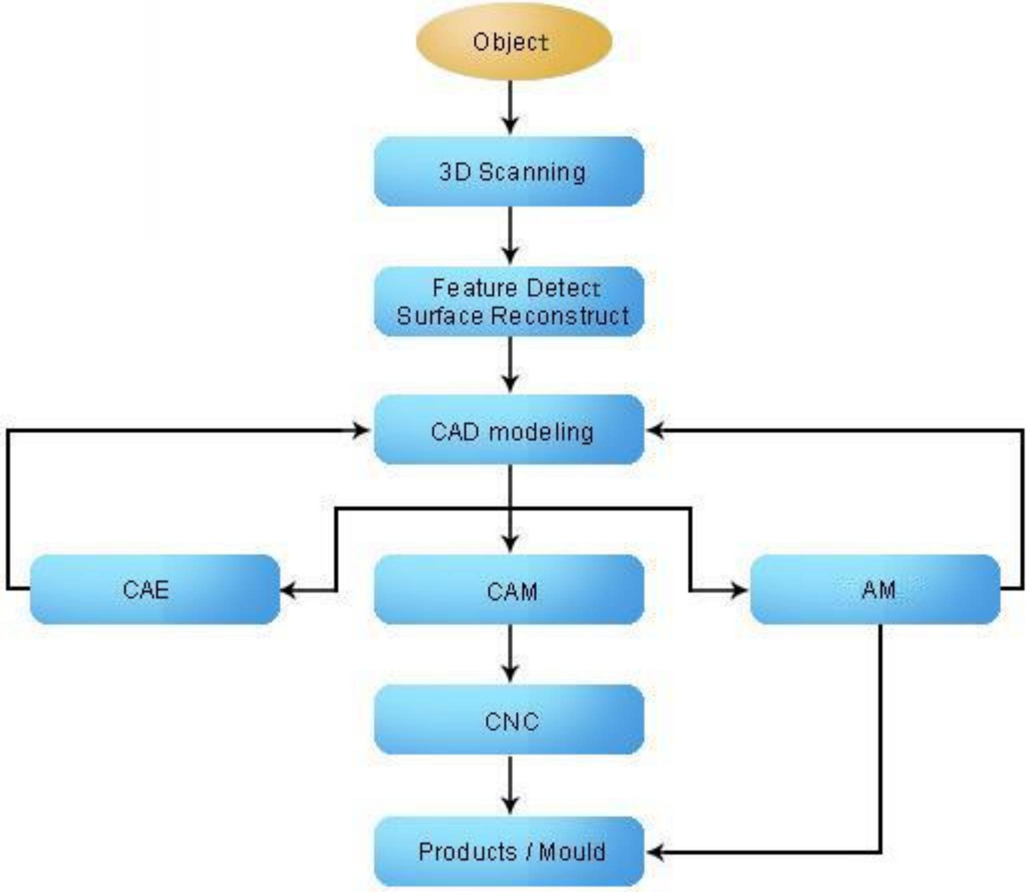

Figure 2.1. Reverse Engineering Flow Chart (©i-CAD Engineering Solutions)

The model can be used for computer-aided engineering (CAE) applications such as finite element analysis (FEA). An FEA package such as Ansys can be used to predict stresses on mechanical components as well as deformation and safety factors. The use of FEA is preferable when the original material specification for a component is not available, otherwise an incorrect material could be chosen for manufacture and lead to component failure. Once a simulated material has been tested, it can either be selected for manufacture, if it is suitable, or if it is not, then another material must be selected or the CAD model must be altered to meet the components operational requirements.

Computer-aided manufacture (CAM) refers to the use of software for the control of machine tools and other machinery in the manufacture of parts. Traditional manufacturing methods such as a Computerised Numerical Control (CNC) milling machine can then be used to produce the component.

AM can be used to rapidly produce prototype parts which can be tested, or otherwise implemented, into the manufacturing process. AM and its uses in manufacture will be discussed further on in this thesis (Chapter 3).

2.2. Geometry Collection

In order for a component to be digitised and made into a workable CAD model, its features and dimensions must in some way be measured. There is a variety of techniques available to achieve this. An object can be measured manually or the use of systems such as measuring machines or scanners can be considered as discussed below.

It should be noted that when scanning a part to gather 3D data from it, if there are damaged or missing areas on the part, these too will be scanned as it is just geometry data to a scanner. There is thus a need for human intervention to realise these parts are damaged or worn and compensate as required. The same can be said when gathering measurements manually. Thus on occasion, an understanding of the requirements of a part is needed, to recognise when a part is worn for example.

2.3. Manual Geometry Collection

A traditional method of gathering measurement data from a part is to use conventional tools. These include vernier callipers, rules, micrometers, radius gauges and thread gauges. These measurement devices allow engineers and machinists to determine accurate lengths, diameters and other dimensions of objects. It is a simple process when used on a part with no freeform surfaces, but becomes more time consuming when the part is complex. A freeform surface is neither planar nor quadratic, i.e. it is not a recognisable geometric shape. If there are surfaces that are freeform then alternative methods of geometry collection must be used.

The disadvantage with manual geometry collection is that it does not produce a 3D model. This has to be done manually using a CAD package and the data gathered from measuring each feature.

2.4. Contact Methods

Coordinate measuring machines (CMMs) use a probe mounted on three perpendicular axes (x, y and z), each axis has a reference standard (Figure 2.2 [7]). The probe is used to gain a set of coordinate points as it moves across the surface of the part to be measured. The coordinates are determined as the probe moves each axis relative to its standard, thus an accurate set of data points can be generated. The CMM can either be operated manually to manoeuvre the probe around the object, or set to automatic and it will collect the data points along a set route [8].

Figure 2.2. Three Axis Coordinate Measuring Machine (© WENZEL®)

CMMs are available with more than three axes and also come in other setups. Multi-axis mechanical arms are used with the probe mounted on their end (Figure 2.3 [9]). Angular measurements are taken at each joint to calculate the position of the probe tip. Such arm CMMs are often used where their portability is an advantage over traditional fixed bed CMMs. Due to the fact that the arm mounted probe has more axes of freedom, it is highly flexible and capable of reaching sections of complex components which fixed bed, machines with less axes would not be capable of. The accuracy of such arm mounted probes are to within 0.1mm, often better [9]. A disadvantage of the arm mounted probes is that they are not automatic, thus each data point is generated manually which is time consuming. Accuracy and reliability of touch probe systems for single point measurement typically exceeds that of optical scanners [10].

Figure 2.3. Portable Arm Mounted CMM

2.5. Laser Scanning

Laser scanners are in common use within industry. They are a non-contact method of geometry collection and can obtain a large amount of point data in a short time [11]. When the laser light is projected onto the object, the dimensions of the object are determined by triangulation. If light arrives at a point on a surface from one direction, and if that light is seen from another direction, the location of the point can be inferred. This is known as triangulation [10] .

A laser scanner can be set up to measure surface points of multiple features by following a single scanning path. The laser used is a line of light, rather than a single point. This makes it a popular choice for RE applications, scanning freeform surfaces in particular. Laser scanning is limited by factors which do not affect contact methods such as surface colour, reflectivity and transparency. It also has limitations on collecting point data on features which provide occlusions and obscuration, such as holes or extrusions (Figure 2.4 [8]). The object to be scanned may occlude both the laser and the camera from viewing different surfaces of the object. Though there are differing quality products, generally laser line scanning is considered less accurate than CMMs [12].

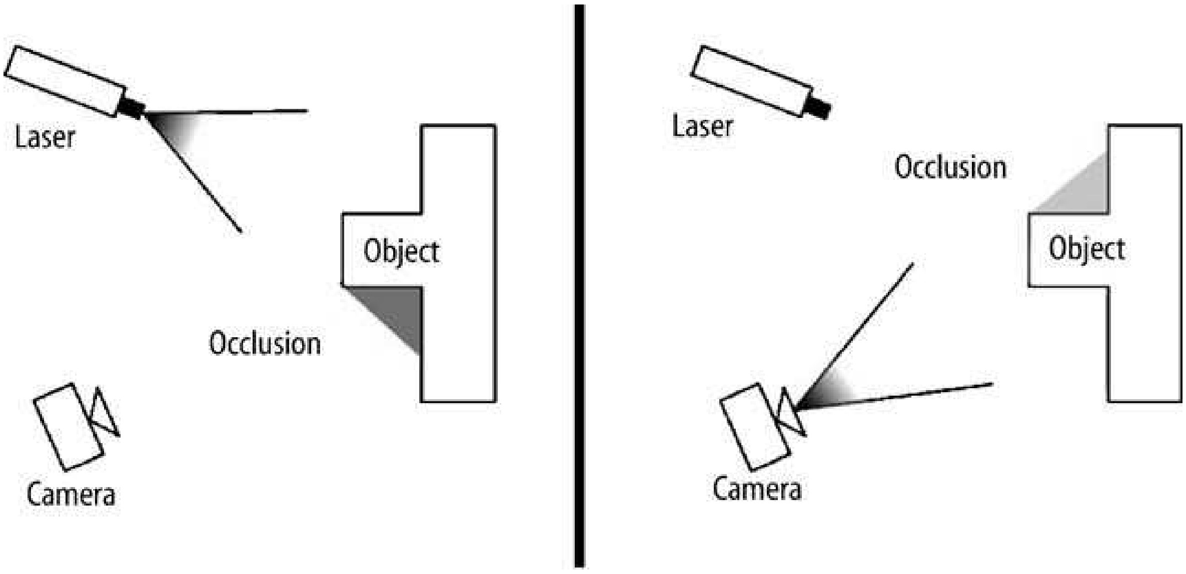

Figure 2.4. Occlusion occurring with Laser Scanning an Object with Holes or Extrusions

As discussed previously, a comparative test of available scanners is presented in Chapter 6.The software for using structured light scanning can also be used for laser scanning, which has been used in a study for designing a low cost scanning system [13]. The software is the DAVID laser scanner is used in conjunction with a red laser line (650nm wavelength), a Logitech Webcam Pro 9000 high-definition video camera, and a background panel which contains the control points. The laser was mounted on an axis which used a mechanical system to control the laser movement, allowing it to be moved around a constant axis at varying speeds. A programmable interface controller (PIC) was used to control the mechanical system. The rotation and speed of the laser were preprogramed and the system was automated. A general view of the system setup is shown in Figure 2.5 [13].

Figure 2.5. Laser Scanning System by Akyol, O. & Duran, Z.

The results showed that the laser scanning setup is capable of a precision between 0.1 – 0.2 mm, though the scanning sensitivity and resolution is proportional to the resolution of the camera used. The data is produced with a spatial data accuracy of 0.59 mm. It is however limited by object size as it must be smaller than the calibration board used with the system [13].

While the results of this study are encouraging for the availability of low cost scanning systems, the system designed was done so by skilled and knowledgeable individuals in the subject. Due to the level of skill required to set this system up, it is not a suitable scanning option for an individual inexperienced in scanning technologies, it is not a ‘plug and play’ device.

2.6. Combination Scanning

Use of a CMM, such as an articulated arm with both a probe and an inbuilt non-contact scanner has become popular. This method of gathering data points uses the best features of both contact and non-contact scanners. It is accurate, fast and flexible [10]. An issue with CMM is that it has to make contact with the object, and so if the part does not have a hard surface and is flexible, then this can lead to inaccurate data points. By introducing a scanner to the articulated probe arm, flexible sections of the object can be scanned without deflection.

The FARO ScanArm (Figure 2.6 [14]) is such a contact/non-contact measurement system. It has the combined advantages of using a probe mounted on a mechanical arm, ideal for gathering data points on complex and difficult to reach features, as well as a laser line probe to scan in volumes of data on the component features. This can be done interchangeably without having to remove either probe. Soft, deformable, and complex shapes can be easily inspected using the laser probe, thus never having to come into contact with the part being scanned. It has an accuracy of ±35μm and a scan rate of 45,120 points per second [14]. The problem with a high end measurement device is the cost, being $40,000 (2015) [15], not including the software CAM2 Measure 10, which is to be used in conjunction with the device.

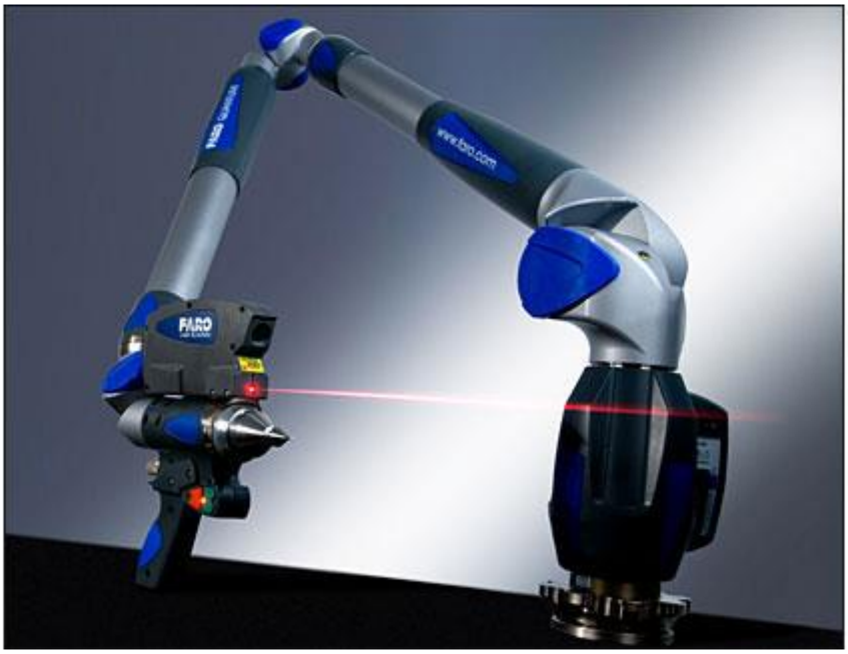

Figure 2.6. FARO® Edge ScanArm HD

2.7. Structured Light

Structured light scanning projects a light pattern onto the surface of the object to be scanned and an image of the resulting pattern is reflected by the object and picked up by a camera. The light projector and the camera are at known angles from one another allowing the image to be analysed to calculate the coordinates of the data points of the surface geometry [8]. The dimensions of the object are calculated by triangulation, in the same way as laser scanning, though instead of a line of light, a coded light pattern is used [10].

CronNos3D is an optical 3D colour scanner with a preconfigured scan area (Figure 2.7 [16]). It is used for capturing the surface geometry of parts, which are automatically aligned as each data set is captured from multiple angles, until a full model is created. It has an accuracy of ±40µm, though this is obtained by the scanner having only a single pre-set scan area, meaning that it is calibrated for the scanning of objects of a similar size. The preferred size is decided at the time of purchase. This somewhat limits what can be scanned as parts which are larger or too small from the specified area, then accuracy is lost or full scans cannot be completed, although there is a version of the scanner called croNos3D Dual, which addresses this issue by having two sets of pre-set scan areas, one large and a smaller one [16].

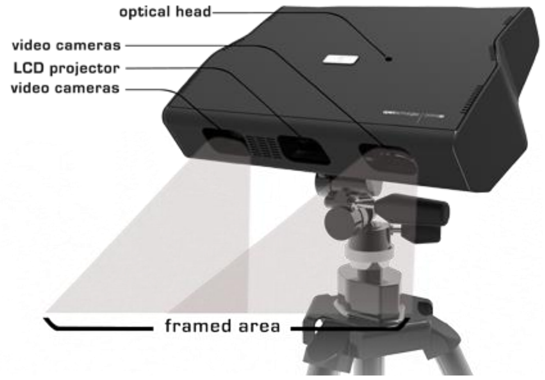

Figure 2.7. CroNos 3D Optical 3D Scanner (© open technologies)

The software that the author has access to works on the same principle as the CroNos 3D, though it is not a pre calibrated unit, i.e. the camera and projector are separate entities which need to be triangulated during calibration. This method will be further explored in Chapters 5 and 6.

2.7.1. Infrared Structured Light Scanning

Infrared Structured Light (IRSL) scanners use an infrared (IR) laser beam to generate invisible patterns. This method is widely used for 3D scanning, and is used to overcome the limitations of structured light scanners which use projected visible light. These visible light scanning methods often struggle with reflective surfaces (Figure 2.8 [17]) [18]. By using IR to create the structured light patterns, and by use of an IR sensor (camera), the radioactive properties of the object being scanned are exploited to collect geometries of surfaces that are normally impossible to scan using visible light sources. By using this technique, a clear glass was scanned in a study with success and with a good result of accuracy, with a tolerance of ±0.2mm (Figure 2.9) [19].

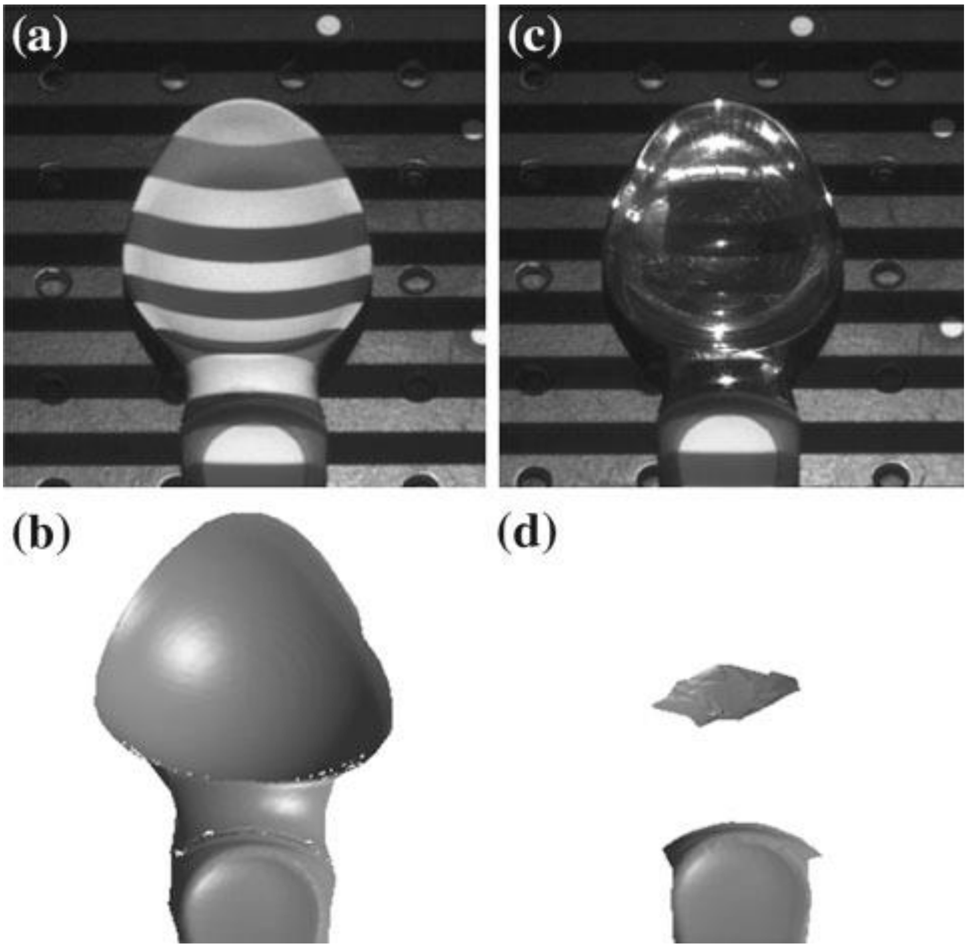

Figure 2.8. Comparison of Visible Structured Light Scanner on Reflective and Non-Reflective Surfaces (a) non-reflective surface (b) non-reflective surface scan (c) reflective surface (d) reflective surface scan

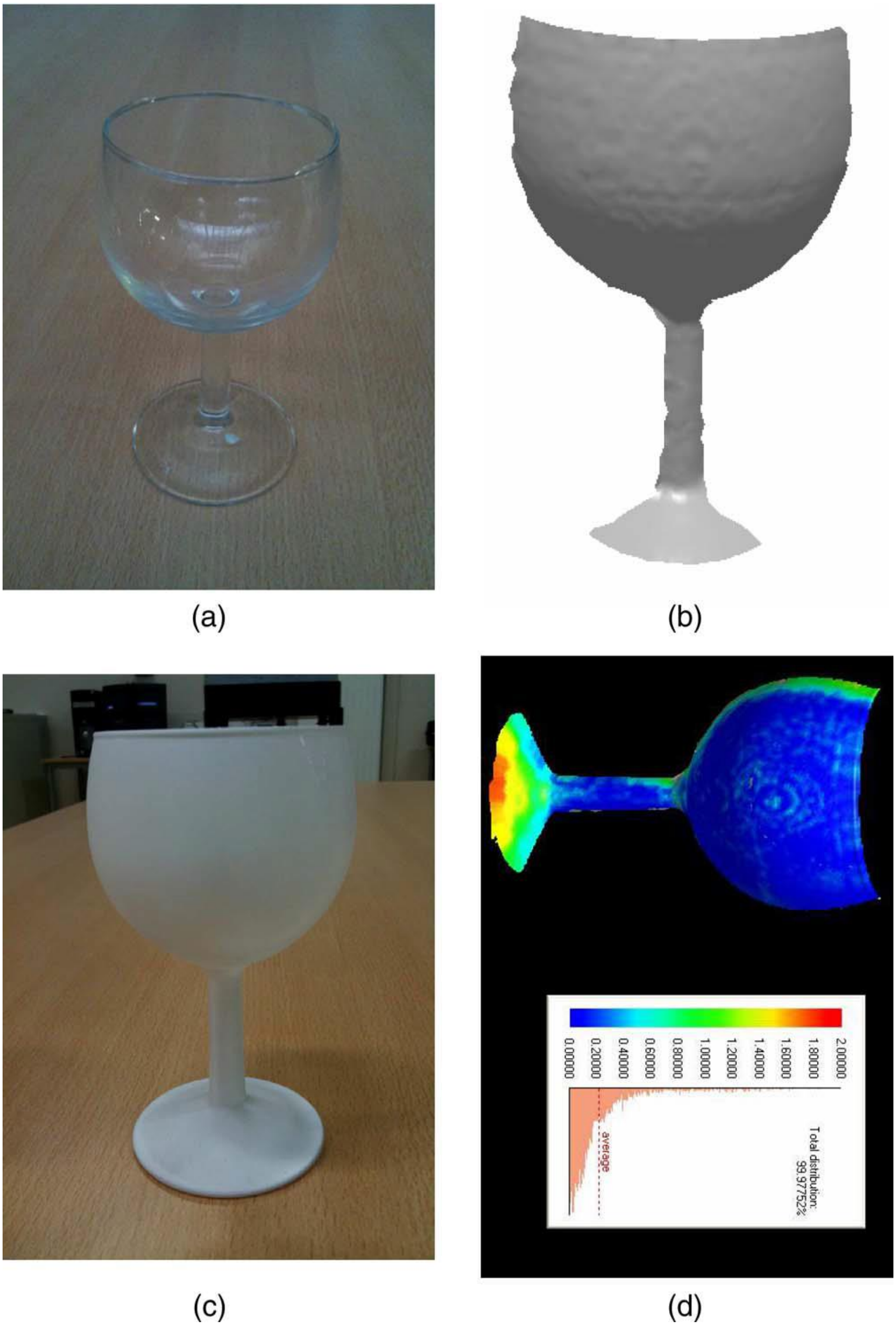

Figure 2.9. Experimental Results. (a) Original glass. (b) Original glass reconstruction by the shape from structured heating. (c) Glass after being coated with spray. (d) Three-Dimensional reconstruction and error map, scale from 0 to 2mm.

2.8. Photogrammetry

Photogrammetry uses a digital camera to capture 3D point cloud data. It is commonly used for inspection purposes, and incorporates targets which are placed on the component to be examined. These targets are used as a multi-point tracker to create *xyz* coordinates and imported into inspection software such as Geomagic Qualify, NRK, or GOM Inspect to be compared against the components CAD geometry. It is also used to reconstruct 3D point clouds from the two-dimensional (2D) images, a method that is improving rapidly. Photogrammetry has potential because it removes the high-cost barrier currently inherent with most high accuracy scanners, especially since most people have access to a good quality digital camera [10].

An old engine part was digitised into a 3D model using CAD package Agisoft Photoscan (Figure 2.10 [20]) showing what photogrammetry is capable of, using only a camera and a software package. However, this particular software is not free, it is $179 for the standard edition and $3499 for the professional package [21].

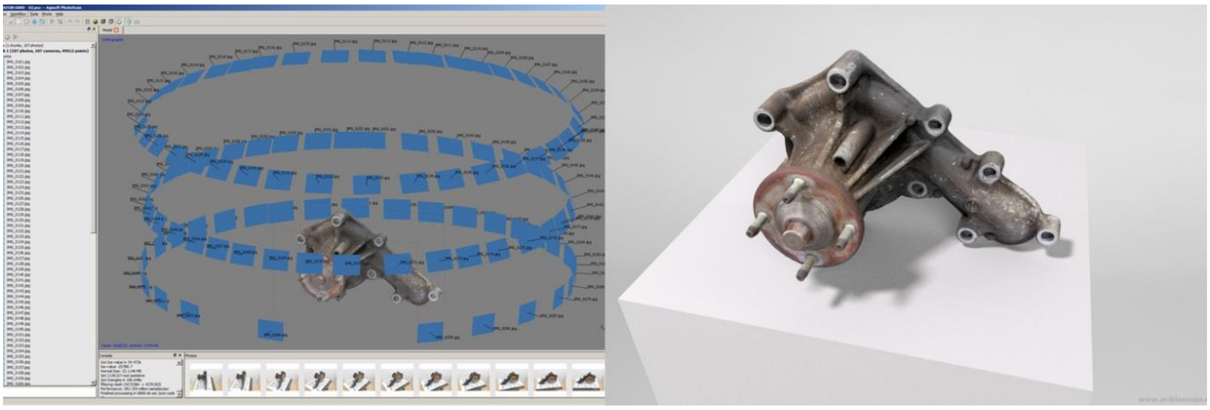

Figure 2.10. 3D Photogrammetric Scan of an Old Engine Component using Agisoft Photoscan

The downside of close range photogrammetry is that it is generally considered to not be very accurate when compared with other techniques such as CMMs. Though it is possible to produce 3D models with accuracies greater than 1mm [22].

2.9. Computerised Tomography

Computerised Tomography (CT) is best known for its uses in the medical field. Though it has been applied in the reverse engineering process to produce a 3D visualisation of the internals of an object. Its working principle is to pass a thin X-ray beam through one plane of an object, which is mounted on a single rotational axis(Figure 2.11 [8]). This produced a cross sectional image which can be modelled together layer-by-layer as the thin X-ray beam is projected at the object from multiple angles [8].

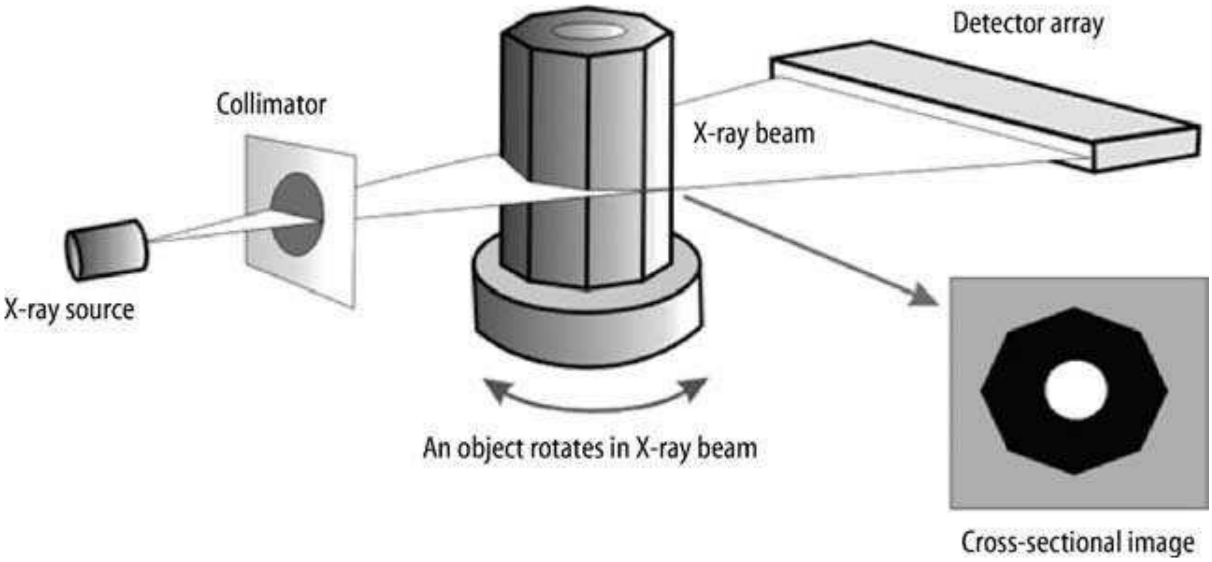

Figure 2.11. Working Principle of CT Scanner

It is capable of producing highly accurate 3D models of an object and its internal features, without it ever having to be taken apart (Figure 2.12 [23]). CT is a powerful technique for reverse engineering applications, however it is the most expensive in terms of both hardware and software [8].

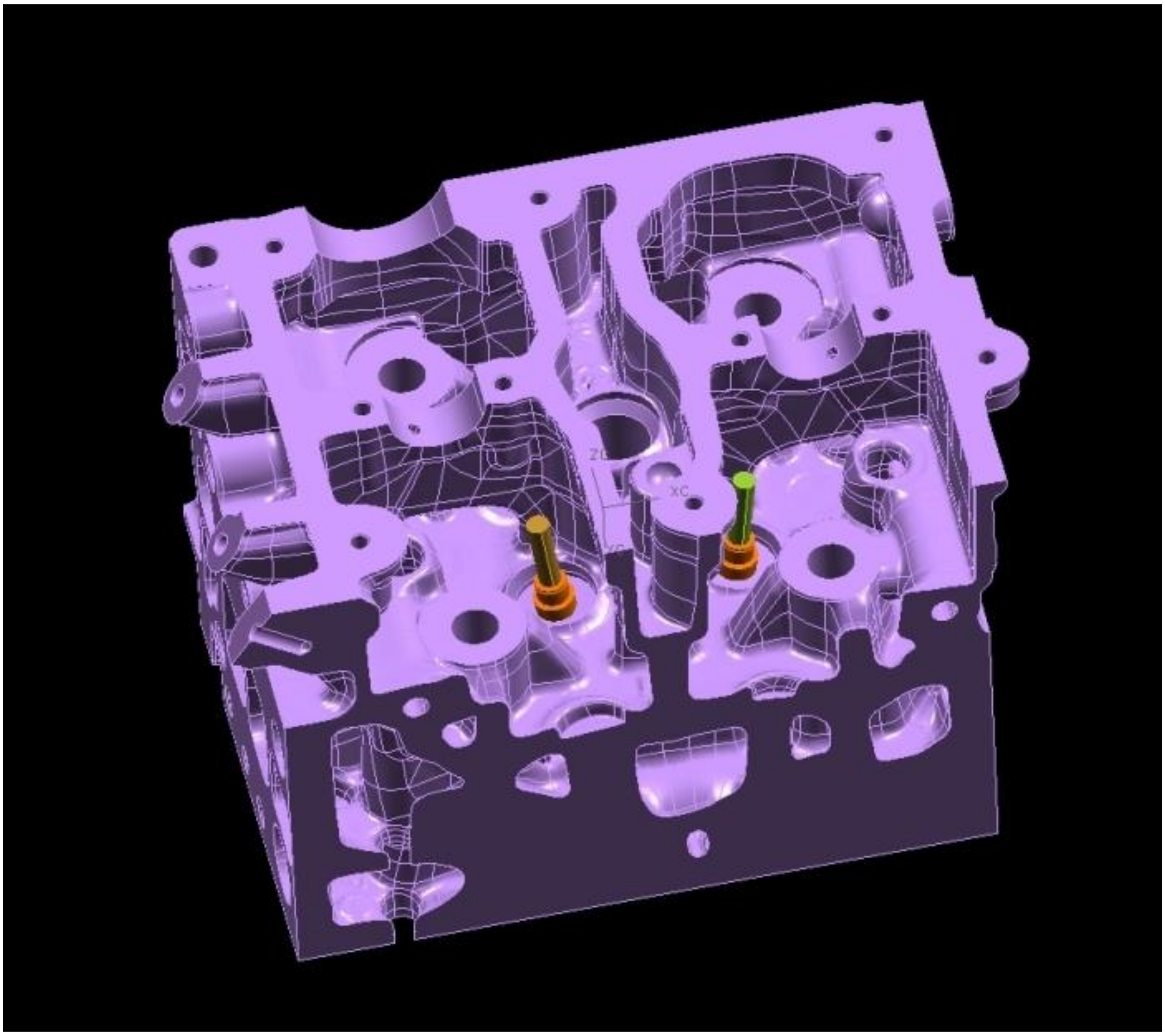

Figure 2.12. Model of Component Scanned using CT (© Microvista)

3. Additive Manufacturing Technologies

AM is considered to be one of the most important material processing technologies in development that will drive the future manufacturing industry. It can produce parts with complex internal and re-entrant features and so many of the traditional Design for Manufacture (DFM) principles no longer apply [24].

AM is not restricted to just one method of production, there are various processes which fall into this class of manufacturing and the main differences and advantages and disadvantages are explained in this chapter.

3.1. Stereolithography

Stereolithography (SL) was the first AM rapid prototyping technology [25]. The machine consists of (Figure 3.1 [26]):

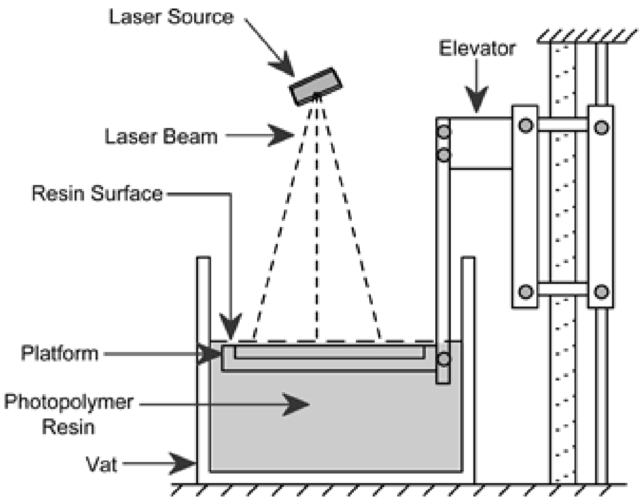

Figure 3.1. Stereolithography Apparatus

- A platform which can be moved vertically (z axis) within the vat which contains the photopolymer resin.

- A vat which is filled with the liquid resin.
- An ultraviolet (UV) laser whose beam can be controlled in the x-y directions.
- A computer with software which controls both the laser and the platform.

The liquid resin, which is a photopolymer, is cured or hardened by the light from the UV laser. To manufacture an object, the platform is first lowered into the photopolymer tank so that there is a fine layer of the liquid above it (usually between 0.05 – 0.15mm). The UV laser then creates the first layer on the platform by tracing the cross sectional area of the layer into the polymer, which cures and hardens. The platform is then lowered further and the next layer is cured and bonds to the first layer. The process is repeated layer by layer until the complete model is made and is fully submerged in the tank. The platform is raised to expose the object, which is rinsed with a liquid solvent to remove any excess resin. Finally it is placed in an UV oven for post processing curing.

SL produces parts of a high surface finish, though it is dependent on the quality of the machine. The process is ideal for prototyping as it produces highly accurate and durable parts fairly quickly and in a relatively inexpensive manner. The manufacturing time for small parts (150x150x150mm) on a small machine can be around six to twelve hours, though for larger parts over a metre to be made on a large machine, it could take days, though this is also dependant on the layer thickness used. This may seem like quite a long process but by contrast to other methods it does not require a mould to be made and a production line set up so will save time overall. Though if a part is to be made in large quantities and is not so complex that it can be made using more conventional processes, then it may be more time and cost effective to have a component made using these methods [27].

3.2. Selective Laser Sintering

Selective laser sintering (SLS) uses a CO_2 laser to fuse powder layer by layer until the desired part is made. A typical SLS machine consists of multiple components (Figure 3.2 [28])

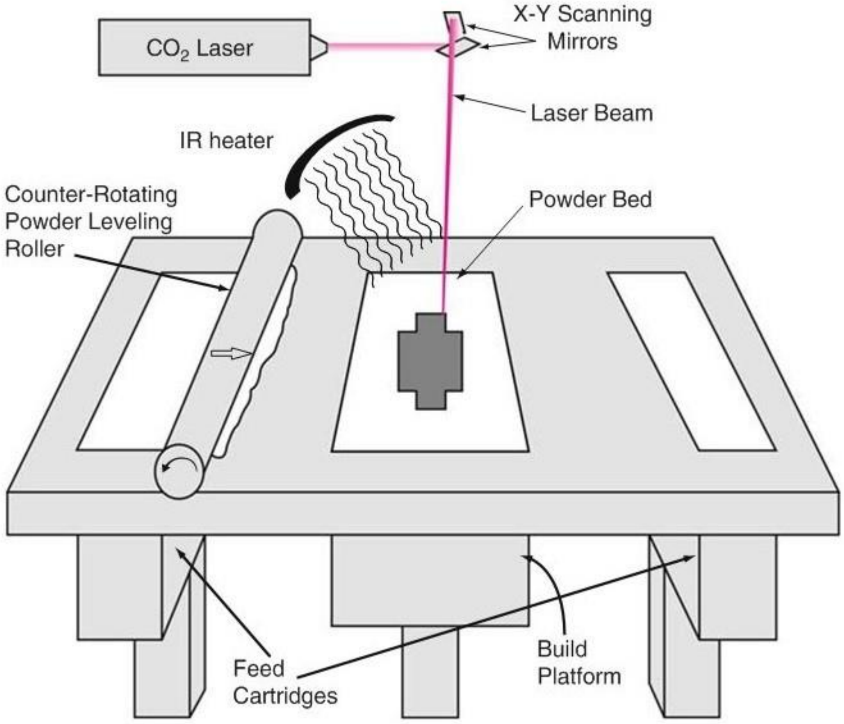

Figure 3.2. Selective Laser Sintering Process

The system is enclosed within a chamber that is used to increase the nitrogen concentration within the build area to reduce oxidation and to prevent the degradation of the powdered material. The feed piston is raised by a small amount and the counter rotating roller pushes the powder over the build platform, levelling the powder as it goes. The IR heater keeps the temperature within the chamber to just below the melting point of the powder. By doing so it reduces the power requirements of the laser to melt the material. It also prevents the part from warping by reducing non-uniform thermal expansion and contraction from high temperature differences. In some machines the build platform is also heated by resistive heaters around the platform to reduce these effects. The laser will trace the first layer cross section, with the powder around it remaining loose while it is fused. The platform is lowered by one layer thickness and the roller spreads new powder from the feed piston over the top of it then the next layer can be fused to the preceding layer. The loose powder acts as a support structure for the sintered part and the process continues until the full component is built. Once complete the part is left to cool until it can be handled and so that when exposed to the ambient room temperature it will not undergo thermal contraction and warp the part. It can be removed from the bed and the loose unsintered powder cleaned from it, then any finishing processes can be applied if necessary [28].

SLS is an advantageous manufacturing method for intricate parts which would otherwise be near impossible or highly work intensive using traditional methods, which would require multiple steps to create the finished product. It may be very useful for producing intricate parts, however it still has some drawbacks. When sintering each layer the heat in the object being fused can lead to heat spots which cause warping of the original geometry, so care must be taken with temperature control of the enclosure.

3.3. Fused Deposition Modelling

Fused Deposition Modelling (FDM) uses an extrusion process to build 3D models. It uses material in the form of filament and in modern desktop printers is stored on a spool. The filament is fed into an extrusion head and heated to a semi liquid state, the extruder uses a fine nozzle to deposit the material (Figure 3.3).The material cools by air convection usually provided by small fans mounted on the side of the extruder. The nozzle follows a preprogramed path generated by a compatible software to generate the first layer, moving along the X-Y plane. The filament cools quickly and solidifies and the model is built up layer by layer [29].

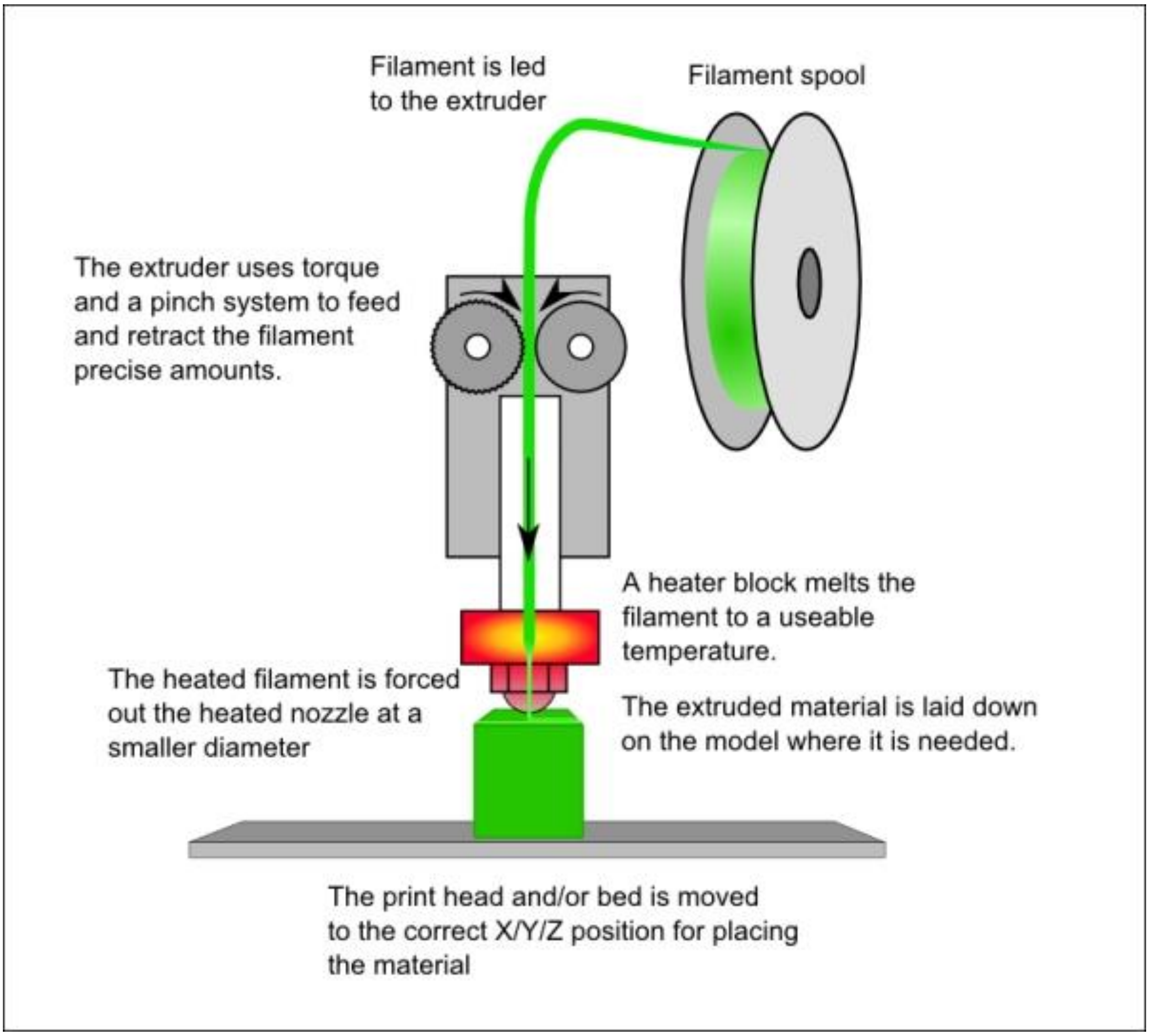

Figure 3.3. The Basic FDM Process (© RepRap)

When building geometries which have overhanging features, the printer will build a support structure from the base of the print bed, to the height of the feature so that the model will not collapse when printing into mid-air. Often in commercial FDM machines the support structure is built using a different material from the part, this allows for easy removal, though it requires a dual print head. Soluble support material is available which requires the dual heads, though breakaway supports can be incorporated into the print using a single material [28].

FDM can quickly fabricate functional parts with minimal wastage, with only support structure as waste. This means that there is little to no post processing necessary. However, it is a slow process as the speed is restricted by the extrusion rate of the print head and the entire cross sectional area of the part needs to be filled with an internal structure for strength, if it is not being built as a solid object that is, which takes longer. It is also susceptible to unpredictable shrinkage as the extruded material is cooled rapidly resulting in stresses through the part. Though with experience users may be able to compensate these by adjusting the process parameters of the machine [29].

The parts which are built are suitable for models which do not require any physical requirement to be met. They are used also for prototyping a design and used in analysis and functional testing. The models produced on the FDM machine are also used as patterns for vacuum forming, investment casting, sand casting and moulding [29].

4. Traditional Manufacturing Methods

4.1. Metal Casting Processes

The process of casting metals requires the use of a mould. The mould contains a cavity which determines the shape of the part to be manufactured. The mould can be made of different materials such as sand, plaster, ceramic and metal. In the casting process, the metal is heated to a liquid state and subsequently poured or otherwise directed into the cavity of the mould. The mould used can be either open (a) or closed (b) as shown in Figure 4.1 [30]. With an open mould, the molten metal can simply be poured in, whereas with a closed mould it requires a passageway, called a gating system which permits the metal to flow into the cavity. A closed mould is used much more frequently in industrial processes as more complex shapes can be made with this mould type. Once the molten metal is inside the cavity, solidification begins as it cools down. Time is required for this stage of the process as a considerable amount of heat is given up as the metal solidifies.

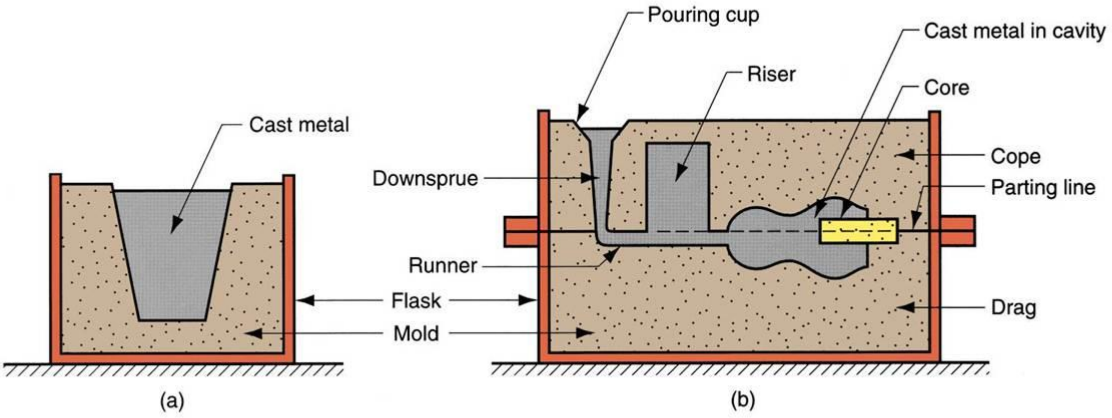

Figure 4.1. Open and Closed Moulds

When casting metals, there is the option of what kind of mould can be used which falls under two broad categories, either permanent or expendable moulds as represented in Figure 4.2.

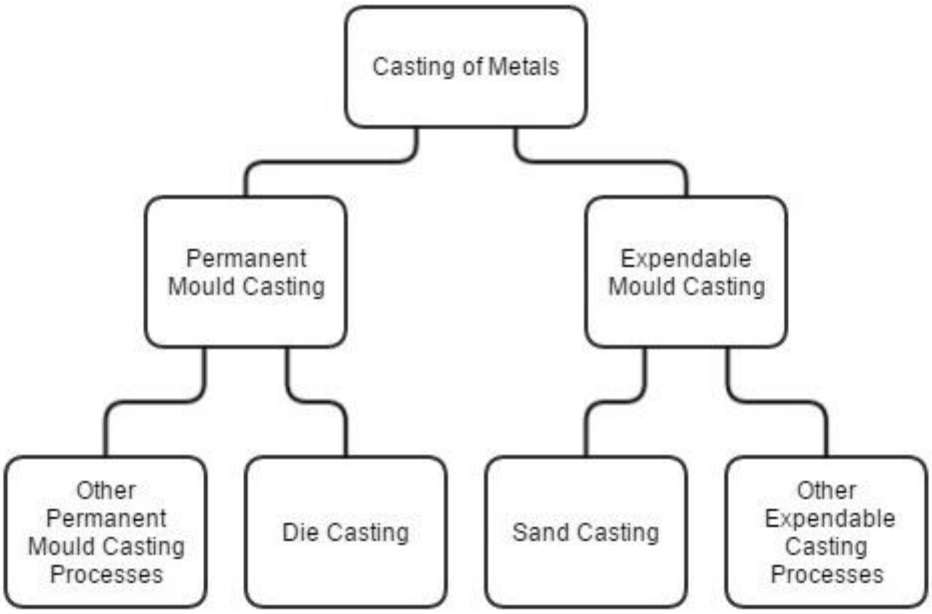

Figure 4.2. Metal Casting Processes

An expendable mould is destroyed once the part is cast and is typically made from sand, plaster or a similar kind of material. This is held together with the use of binder which allows the moulding material to maintain the required shape for the casting. A sacrificial mould is advantageous when an intricate part is designed as it can be split apart as desired to remove the part. Sandcasting is the most common process used in this technique of expendable casting.

A permanent mould is used repeatedly and is made out of metal or sometimes ceramic to withstand the high temperatures of casting. Due to the need of being used multiple times, the mould is often split into two or more parts in order to allow the cast part to be removed. This limits the intricacy of the part that can be designed. Die casting is the most popular method of permanent casting.

With the cast metal cooled it can then be removed from its chosen mould as required. Further processing may be required depending on the casting method used. This could include trimming excess metal from the cast, cleaning the surface of the part, inspection of the product or heat treatment to enhance the properties of the metal as would be required of the product when in use. Machining may also be used to obtain closer tolerances on features of the part, or for the removal of the cast surface [30].

4.2. Expendable Mould Casting

4.2.1. Sand Casting

The mould for sand casting consists of two halves, the cope and drag. The cope is the upper half, and the drag is the lower. These are contained within a box called the flask, which is also in two halves, split along the parting line as seen previously in Figure 4.1. In expendable mould processes the cavity is formed by means of a pattern. Sand is used as it is an inexpensive material with a high melting temperature. The sand typically consists of 90% sand, 7% clay and 3% water, though synthetic version are also used with bonging agents replacing the clay and water. The additional elements in the sand helps it retain its shape of the cavity. The pattern can be made from wood, metal plastic or another material and is in the shape of the desired part to be cast. The pattern is oversized to allow for shrinkage as the metal cools and solidifies and to accommodate any finishing machining processes.

Due to the ease with which wood can be shaped, it is a common material used for the manufacture of the pattern. However, wood has the tendency to warp and also be abraded by the sand when it is packed around it to form the cavity, thus lessening the amount of times it may be used effectively. Patterns constructed from metal are more expensive, though will last longer than their wood or plastic counterparts. Plastics are a compromise between wood and metal with regards to both cost and lifetime. The strength and durability of the pattern material selected is dependent on the volume of castings to be created. This is to minimise cost and production timescales.

The cavity is formed by packing the sand around the pattern, with roughly a half in each the cope and drag. A fine grained sand can be compacted more closely, thus the impression left in the sand by the pattern will be more accurate with a closer surface finish to that of the pattern and also yields a higher mould strength. The pattern is then removed and the remaining cavity is the correct shape for the part. Different metals and alloys have different shrinkage rates that need to be accounted for in the process. The pattern will often be coated with a parting agent to allow easy removal from the moulds. [31]

The cavity supplies the external surfaces of the casting, though there may be internal features required on the part also. These surfaces are created by the use of a core, which is usually made from sand, but plaster, metal or ceramics could also be used. These cores are then located inside the mould cavity.

The molten metal flows into the cavity from outside the mould by means of a channel, or a network of channels known as the gating system. The gating system typically consists of a downsprue through which the metal enters a runner that leads into the main cavity. A pouring cup is often used at the top of the downsprue, also known as the sprue, to minimise the metal splashing and becoming turbulent as it flows into the sprue, shown as a simple cone-shaped funnel. The shape of the pouring cups can differ though, with some pouring cups designed in the shape of a bowl, with an open channel leading to the downsprue.

If shrinkage is predicted to be substantial when casting, there is a requirement for a riser to be connected to the main cavity. The riser is a reservoir in the mould that serves as a source of liquid metal for the casting to compensate for shrinkage during solidification. The riser must be designed to solidify after the main casting so as to satisfy this function.

When the metal is poured into the mould, the gases which occupy the cavity must be able to escape, as well as any heated gases created by reactions of the molten metal so that the metal will completely fill the empty space. When sand casting, the natural porosity of the sand mould allows for the air and gases to escape through the cavity walls, though if finer grained sand is used then it will limit the porosity of the mould. In permanent metal moulds, small vent holes are drilled into the mould or machined into the parting line to permit removal of air and gases [30].

The advantages of sand casting are that almost any metal can be cast, with no limits to part size, shape or weight. It is also a cheap option as there is a low tooling cost and the mould material is inexpensive. It is limited by its relatively rough surface finish which will require some finishing processes. It can be an exhaustive process if done by hand, though this is addressed by the use of sand moulding machines. These machines compact the sand around the pattern instead of having to do so manually. This saves on production times and often increases the quality of parts produced as they are all made uniformly. [31]

4.2.2. Investment Casting

Investment Casting is also known as lost wax casting as it uses wax to create the pattern. The pattern is typically injection moulded into a metal die which forms as one piece, though if the geometry of the part is complex then several wax patterns may need to be made and joined together to complete the pattern. The use of cores allows for any internal features if required, and for high production operations several patterns are attached to a central gating system to for a tree-like structure as shown in Figure 4.3 [32]. This means more parts can be cast in one go and saves time on each individual parts casting.

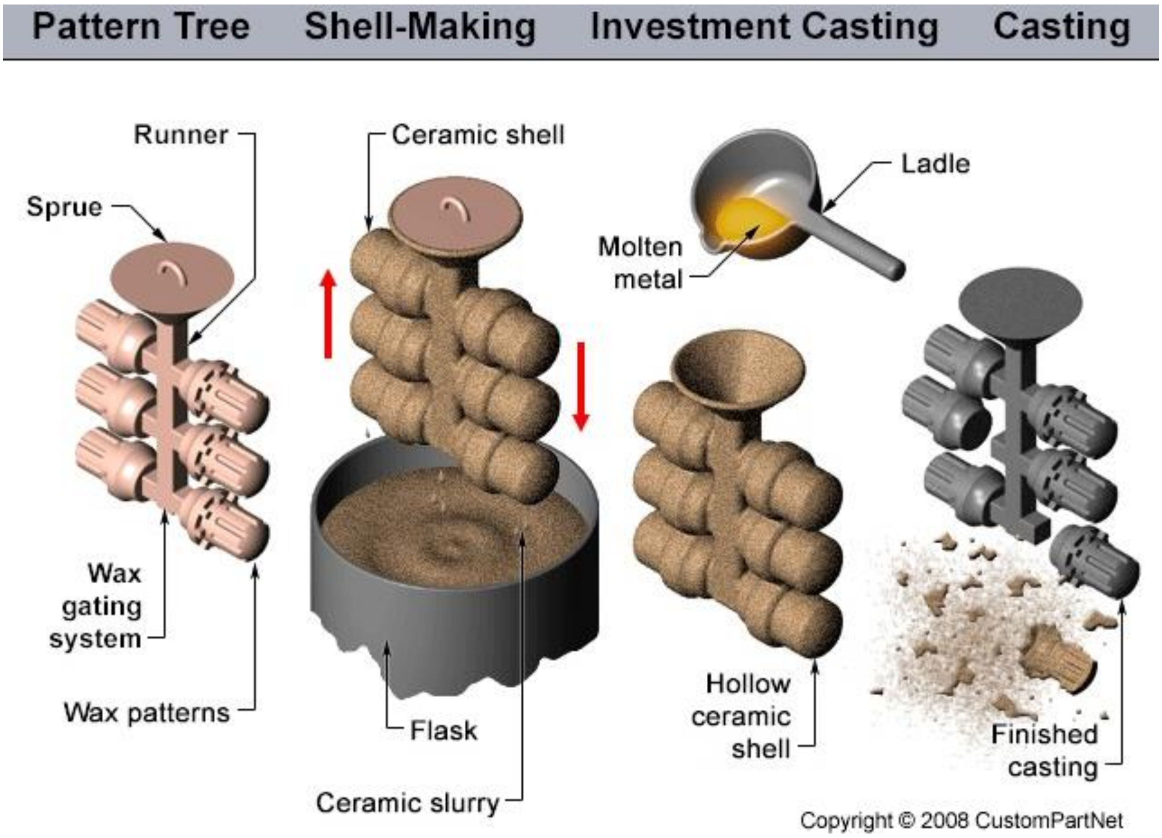

Figure 4.3. Investment Casting Process

The pattern tree can then be dipped into fine ceramic slurry, which is then dried to form a ceramic shell. The fine grain size of the ceramic of the refractory material provides a smooth surface and captures the intricate details of the wax pattern. Multiple layers of this ceramic process may need to be applied until the shell is thick enough to withstand the temperatures of casting. Once the shell is hardened, the wax pattern it was formed around can then be melted out of it, leaving a cavity in its place into which molten metal can be poured under gravity or on some circumstances vacuum or pressure is used.

Once the metal has cooled and solidified, the part tree can be removed from the ceramic mould by breaking it off, often with the use of water jets. Since the mould is broken each time and the wax is melted out, a new wax pattern must be made for each part tree. The individual parts can then be removed from the gating system, either by sawing or cold breaking. Additional machining processes may be required, though lost wax casting produces parts with high dimensional accuracy, and a good surface finish is possible, thus further processing may not be necessary [33].

4.3. Permanent Mould Casting

4.3.1. Die Casting

Die casting is a permanent mould casting technique which employs a metal mould which comprise two separate sections that are designed for easy, precise opening and closing. The moulds are usually made from steel or cast iron and the cavity and gating system are machined into each section to ensure dimensional accuracy and a good surface finish.

The moulds can withstand the molten temperatures of metals such as aluminium and copper-base alloys, as well as cast iron, although the latter requires a high pouring temperature thus it shortens the life of the mould. Steel has a higher pouring temperature than cast iron and so is not suitable for permanent mould casting unless the mould is constructed of a refractory material.

Die casting injects the molten metal into the mould under high pressure. This can be done in two different setups, either hot chamber or cold chamber. A hot chamber machine, as depicted in Figure 4.4 [34], is used for metal with a relatively low melting temperature, such as zinc, tin or lead. The metal is melted in a container, which is attached to the machine, and a piston is used to inject the molten metal under pressure into the die. The pressure is maintained during cooling and solidification. The injection system in hot chamber machines are put under tough conditions as a large portion of it is contiually submerged into molten metal, thus the need for the low melting point of the metals used in this process.

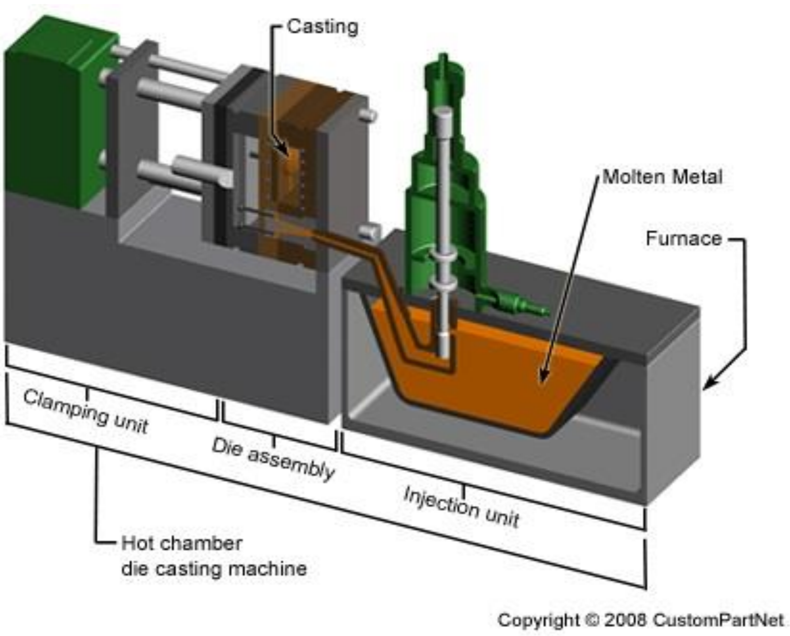

Figure 4.4. Hot Chamber Die Casting Machine

Cold chamber machines differ from hot chamber machines only in how the molten metal is injected into the cavity. Molten metal, heated from an external source, is poured into an unheated chamber, and a piston is used to inject the metal under pressure into the die cavity. The setup is described in Figure 4.5 [35]. Typical metals that are cast include aluminium, brass and magnesium alloys.

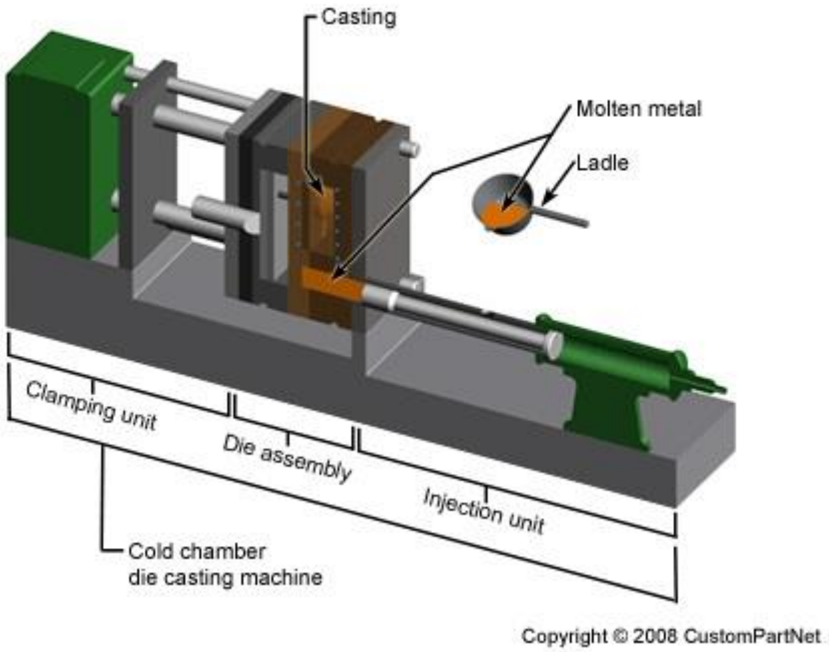

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Figure 4.5. Cold Chamber Die Casting Machine

Once the casting is cool enough, it is removed from the mould by use of ejector pins. These pins push the part away from the mould surface, assisted with the use of lubricants which are sprayed into the cavity prior to casting to prevent sticking. The materials used for making the dies are not naturally porous, vent holes must be included into their design along the parting line to allow the air and gases in the cavity to escape during casting. Once the part is ejected, the metal which has travelled into these vents must be trimmed along with any flash which has occurred.

Flash is the metal which has solidified in the small gaps and tolerances between the dies around the parting line, or around any cores that have been used.

5. Case Study – Uno Coffee Roaster

5.1. Introduction

J.Atkinsons & Co. (Atkinsons) are a Lancaster based coffee roasting company who roast, sell, and serve Coffee, as well as Tea and other related products. They roast their own coffee beans on site with the use of a 1945 14lb Uno roaster for small batches, and also employ a 28lb and a 56lb Whitmee manufactured in the 1930’s to roast larger batches of beans. The use of the older, open flamed machines requires the skill of roasting the beans by sound, smell and sight instead of relying on modern electronic monitoring devices. Among the artisan community, the traditional method of roasting beans is incredibly popular and so the need for the refurbishment and reproduction of older machines is increasing.

Atkinsons are in possession of a 1919 7lb Uno roaster that was in need of repair and replacement components. It was in relatively good condition considering its age but is missing a few key parts that are critical for its continued operation. However, due to the age of the machinery, there are no documents relating to its construction, assembly or part design. As such, it was required to assemble the individual parts using the 14lb Uno as a guide as the two models are relatively similar, sharing some common components with mostly only minor changes as they are scaled up for the larger roaster. Once assembled, as shown in Figure 5.1 below, missing parts could be more clearly identified.

Figure 5.1. Assembled 7lb. Uno Roaster

5.2. Fan Pulley Assembly

With the roaster assembled, it was easier to establish which parts were missing or not fit for purpose. The first issue to arise was a complete lack of components to get power to the fan belt pulley shown in Figure 5.2. The motor transmits power to the lower clutch mechanism using a v-belt and pulley system, which should then travel to the fan belt pulley via a 90 degree turn using two holes in the bottom right of the main body. The location of these holes can be seen circled in Figure 5.3. However, there are no parts spare after assembly or documentation to show what is used to do this. V belts are capable of numerous setups to deliver power to the required shafts that lie on a non-parallel axis.

Figure 5.2. Fan Belt

Figure 5.3. Circled Location of Holes on Uno Assembly

In order to overcome this problem, a set of pulleys referred to as idlers had to be designed to guide the belt around the 90 degree bend and to the fan pulley. This type of setup is known as a mule drive, an example of which can be seen in Figure 5.4. Mule drives may be defined as those drives in which the shafts may be at right angles to each other and in the same plane as shown below. It is necessary in this type of drive to provide two idlers to accomplish the belt bend and twist as shown [36].

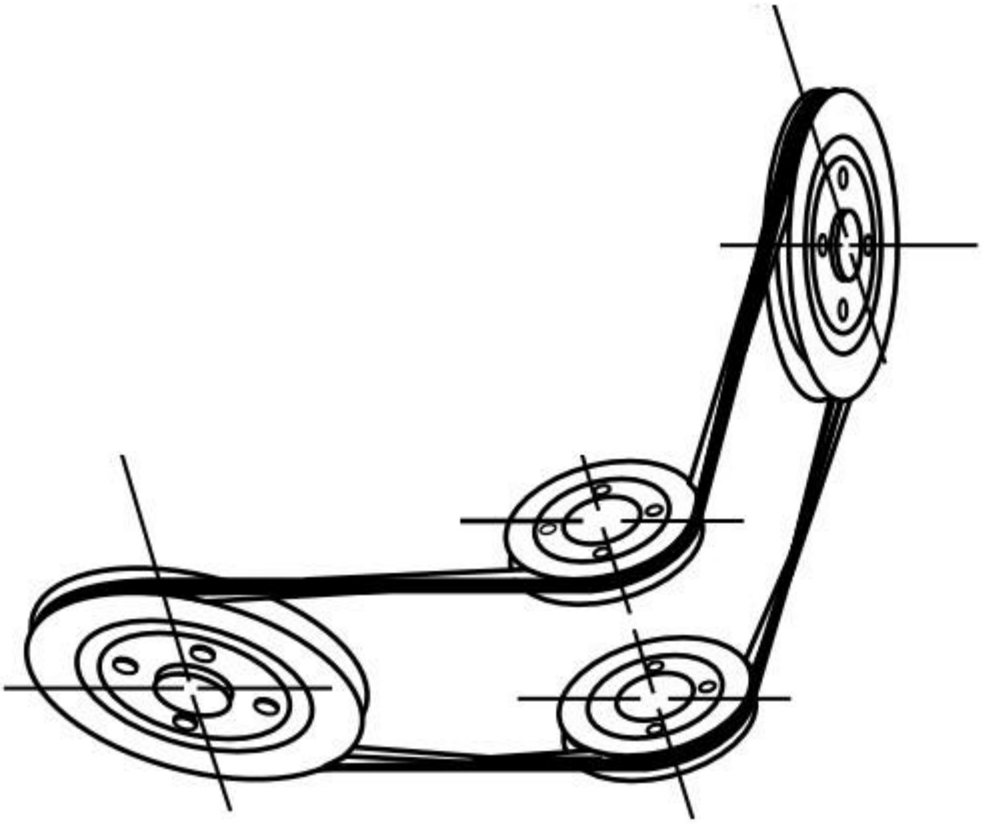


Figure 5.4. Mule Drive

By using the basis of a mule drive, a pulley system was designed to use the existing holes and positions of the other pulleys. It consists of two idlers (pulleys), a shaft and a bracket as shown in the SolidWorks render in Figure 5.5. Both the shaft and the idlers were toleranced to accommodate a 6900 ZZ deep groove bearing and the use of standard internal and external circlips. The pulley accommodates a standard SPZ v-belt profile, and the bracket was slotted in several key areas to allow fine adjustments so that the belt will run true.

Figure 5.5. Fan Pulley Assembly

The design of the fan pulley system was undertaken with a number of factors in mind. The design had to be consistent with the original aesthetics of the Uno Roaster, as a complex or bulky design would not fit in with the rest of the original parts. The machine was designed to be simple, functional and aesthetically pleasing. It is comprised mostly of folded sheet metal, bolts and rivets. Thus, designing a part which is not constructed of simple components would not fit well with the overall look of the roaster.

There were many ways of designing the pulley without changing the aesthetic, but with only the original holes left, any clue as to what mechanisms were in place before, there was no way to exactly recreate whatever system was originally used.

With that in mind, the design was to incorporate the holes as much as possible. As can be seen from Figure 5.6, the holes are not perfectly symmetrical about the horizontal axis nor perfectly aligned level with one another. To address this issue, the use of slots for adjustment was required, and by only using the left hand screw holes, and introducing new ones, the bracket can be fixed to the base level.

Figure 5.6. Original Holes

5.3. Clutch Lever

When reverse engineering specific parts to be remanufactured, there are a number of ways in which to consider the design of the new part. It can be created exactly as it once was, or the same design but in a different manufacturing method, or a different design however still fulfilling its intended function. The levers pictured in Figure 5.7 are part of a clutch mechanism to engage the roasting drum (105mm in length). The lever pictured on the right is an original for another clutching system, but varies from the part to be reverse engineered only in the length of its shaft (125mm).

The original lever indicates that its counterpart would be made from mild steel. It was most likely manufactured by brazing a threaded rod into a knob which was turned on a lathe. This is theorised as brazing leaves a brass colour around the joint that was fixed which stands out from the colour of the mild steel. There exists also, cylindrical tooling marks on the knob that represent the lathe tooling process which was used to manufacture the part.

Figure 5.7. Clutch Levers

Brazing is used to join dissimilar metals by way of a filler metal, usually comprised of a copper base with silver, nickel, zinc or phosphorus additives. It differs from welding as it does not melt the metals to be joined, but rather only the filler. The temperature can range from 900ºF - 2200ºF (470ºC - 1190ºC), though the temperature must be less than that of the metals to be combined. Brazing results in a strong joint when done correctly, often stronger than if the base metal were to be welded [37].

The middle lever pictured is also made from mild steel, and replicates the original design, though it was manufactured slightly differently, by threading the knob onto the shaft. The lever on the left does not follow either the same design or method of manufacture, though it still functions as the part was required to.

The lever could have been made using an AM method but the part is simplistic, however it requires a level of strength at the threaded base to ensure it doesn't bend or break while maintaining the tension in the clutching mechanism. Plastic AM is unlikely to be strong enough, thus metallic AM would be the only option if AM was to be used.

Though it is possible to use AM to manufacture this part, it would not be cost effective for such a simple part. Though each lever is made differently, they all meet the parts functional requirements, which is why an understanding of DFM is required. Otherwise a part can be manufactured to meet the aesthetic requirements, but fail on any strength requirements the part may have.

5.4. Pulley Wheel

The top pulley wheel is attached to the drum, as shown in Figure 5.1. It is in a state of disrepair, and no longer has the ornate pattern that the bottom pulley wheel possesses. Instead there was a plate welded as the internal structure between the base attachment for the shaft and the v-belt profile rim. The rim was bent, buckled and poorly welded in a number of areas and no longer ran true on the shaft. It was effectively no longer fit for purpose as the belt would not be able to stay on it as it turned and its structural integrity was questionable given the cracked welds and visible corrosion.

This part presented the best opportunity to incorporate the reverse engineering process, using 3D scanning technologies, along with integrating AM into traditional manufacturing methods to recreate and produce a final working component.

In order to manufacture a new pulley, with the same geometric features (logo, etc) as the larger one shown in Figure 5.8, the large pulley needed to act as a pattern guide. The desired final diameter (300mm) of the new pulley was determined from the current deformed version.

Figure 5.8. Large Uno Pulley Wheel

Thus, a replacement was required and needs to be modelled in CAD. This in itself presented problems as there are a number of ways to turn the physical part into a 3D model. The options considered are explored for the Uno pulley wheel below.

5.4.1. Manual Geometry Collection

Due to the relative complexity of the part, it is a time consuming task to manually gather geometry data for its reproduction into a 3D model. i.e. physically measuring radius and arc sections, and determining their dimensions and centre points would be incredibly difficult and time consuming.

5.4.2. Scanned Geometry Collection

There a number of ways to scan an object in three dimensions, the result is the same however. Scanning results in either a point cloud of the objects surface, or a polygonal model where the surface is made up of a mesh of triangles. The common file formats produced are *.obj, *.ply and *.stl.

There were two scanning options available to the author, which were used in the reverse engineering of the pulley wheel component; infrared structured light (IRSL) using a device called the 3D Sense, and structured light using the David Laserscanner. Both of these systems were chosen because they represent an inexpensive method to achieve the desired 3D model, less than £500.

5.4.3. 3D Sense

The 3D Sense, a handheld 3D scanning device produced by Cubify, uses two cameras and IR lasers. It works by projecting a patterned IR beam onto the object and this is detected by one webcam, whilst the other webcam translates the surface colours onto the scan [38]. Using the Sense, the model shown in Figure 5.9 was created. The scanning process is simple, from the software there are options to choose whether a person or an object are being scanned, then once in the sub–menus, it is possible to select either full body or head for a person, or small, medium or large for an object. This selection process is more clearly displayed in Figure 5.10 below. Small object option was selected for the pulley wheel as it gave the highest resolution results on the contours of the component, then using the live display on the screen the desired object is picked out from the background. However, the limited frame size of this option meant that it cut off a small portion of the wheel, as can be seen in the scan result. To obtain the best results, keeping the same distance around the object whilst moving smoothly and slowly as to avoid it losing tracking works well. If tracking is lost, a ghost image appears as its last known scanning position, and this must be overlaid with the live display to regain tracking.

Figure 5.9. 3D Sense Scan Result of Uno Pulley Wheel

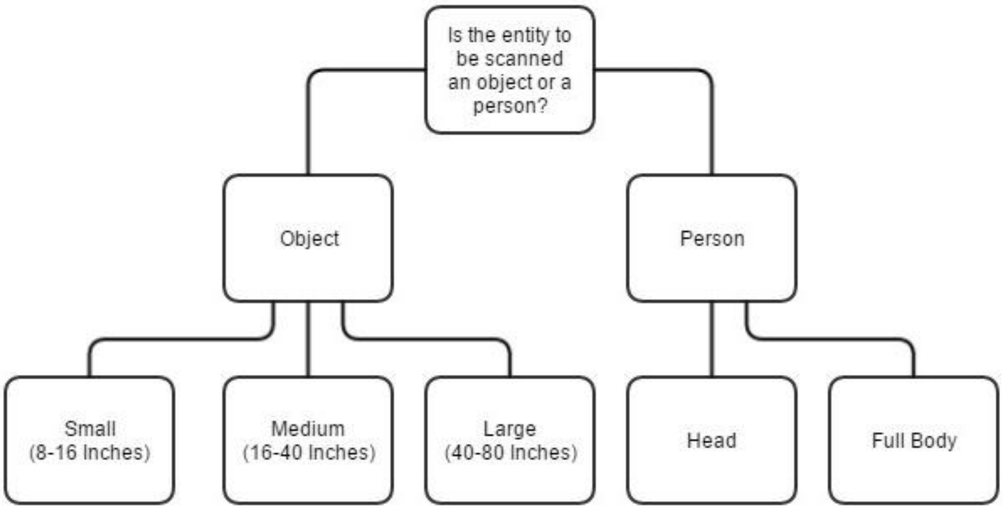
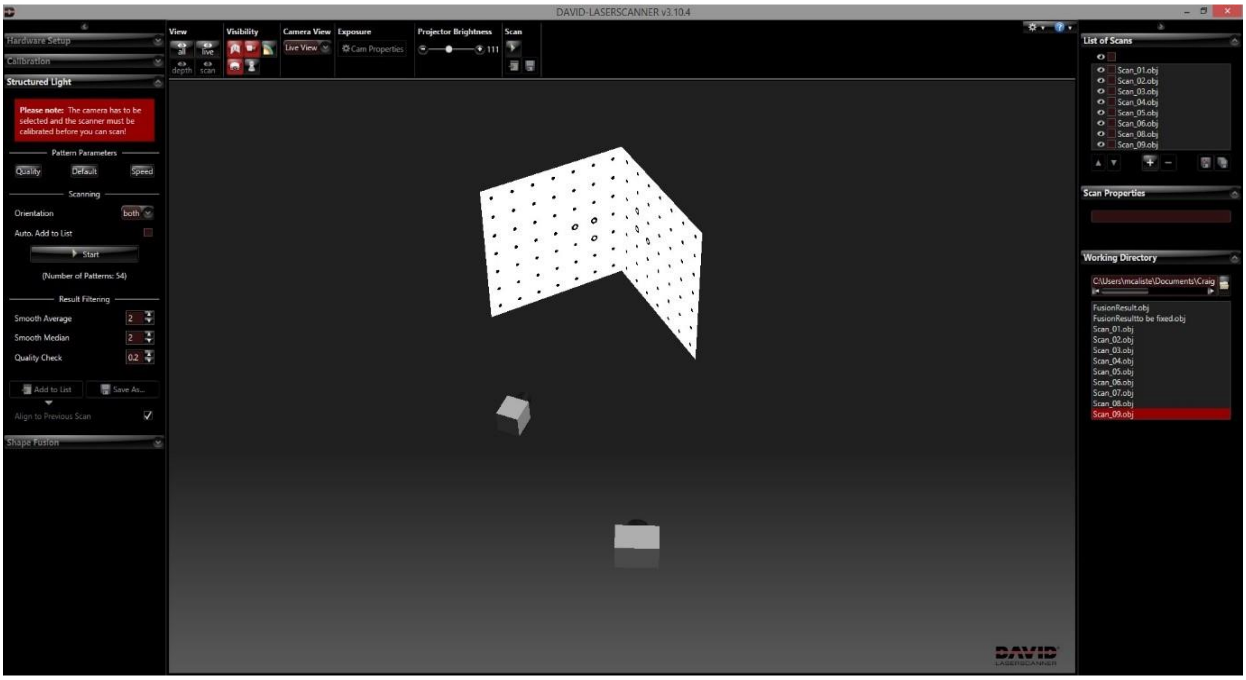


Figure 5.10. 3D Sense Configured Scanning Options

Due to the pulley wheels shape, the 3D Sense had no issues picking up its features from the front or rear view, however it consistently lost tracking on the thinner edge and thus a complete model could not be created. The model shown is simply one face of the pulley which is not of the highest quality in terms of smoothness or quality of definition and sharpness. Even if the Sense was capable of providing a full 360° model of the wheel, the resolution of the scan isn't good enough to be able to reproduce a 1:1 size component identical to the part input to the scanner. It did however cope well with the surface texture, though if this could be because it is a matte surface rather than shiny is unknown, a further investigation is required.

5.4.4. DAVID Laserscanner

Structured light is another option for geometry collection. This is enabled using DAVID Laserscanner software which contains the necessary calibration setup to reference the positions of a camera and a projector relative to one another in 3D space by use of a calibration board as can be seen represented in the software screenshot in Figure 5.11. Once the positions of the camera and projector are realised, the calibration board can be removed and the desired object for scanning can be placed into the crossing paths of the projectors light and the cameras view. Any areas of the object which are not seen by the camera or lit up by the structured light beams will not be present in the scan data. The surface model that is created from the structured light patterns is done so by analysing the deformation of the known pattern that is projected onto the objects unknown surface contours [39].The structured light patterns are made up from straight black and white lines and can be orientated in different ways, i.e. horizontal and vertical. An example pattern is shown in Figure 5.12.



Please note: The camera has to be selected and the scanner must be calibrated before you can scan!

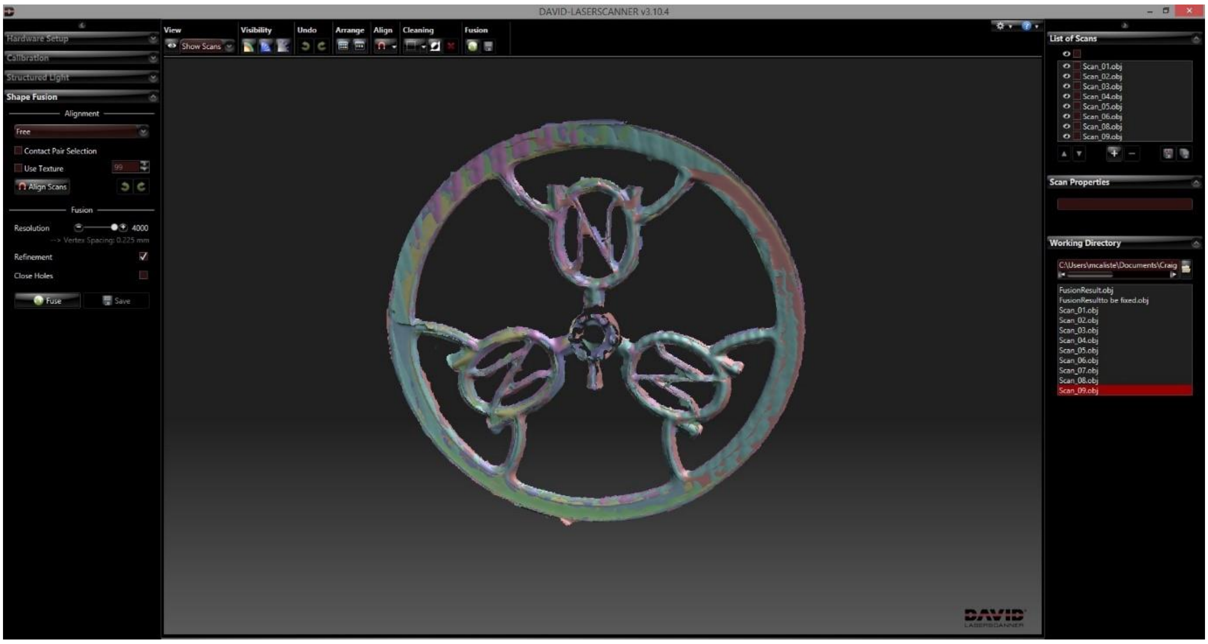
Orientation: both
Auto. Add to List ☐
(Number of Patterns: 54)
Smooth Average: 2
Smooth Median: 2
Quality Check: 0.2
Align to Previous Scan ☑
C:\Users\mcaliste\Documents\Craig

Figure 5.11. David Laserscanner Camera Calibration

Figure 5.12. Structured Light Pattern Example

With the camera and projector calibrated, it is simply a case of setting the structured light options as desired, with regards to how many patterns are to be shown. The more patterns there are, the higher the quality of scan produced will be, however it increases the timescale for each scan. Care must be taken with the brightness of the projector as it can be too bright, resulting in the surface of the part being scanned being too bright for the camera to distinguish details. This can be adjusted easily in the software and may need to vary for different scans if the light levels of the room the scan is taking place in vary. Ideally the scanning should be performed in a darkened room with a black matte background around the object to be scanned as this is best to absorb the projectors light, so that the camera will not pick it up. There are control options for smoothing the scan created as well, in terms of reducing jagged edges and contours of the surface model.

With all calibrations complete, the model must be scanned in stages as this method of 3D scanning is technically defined as 2.5D scanning. This is because it only scans a static surface. In order to get a real 3D point cloud of an object, a rotating stage is best to scan the part from multiple angles, and then ‘stitch’ the individual scanned surfaces together. The software has a function called ‘shape fusion’ which allows manipulation of the scans to clean them up in terms of their smoothness and to delete any unnecessarily scanned surfaces. It also has options on how to orientate the scanned surfaces. They can be automatically aligned with the previous scan, or can be selected individually to align to whichever other previously scanned surface has the most collinear points as the scan. The scans align with a higher accuracy to other scans which share the largest surface area that is similar to that of the scanned object. An example of multiple scans aligned with one another is shown for the Uno pulley wheel in Figure 5.13. Once the scans are complete, they can be merged into one single scan file by using the ‘fuse’ option in the software. This will result in a single *.obj file of the part as shown in Figure 5.14. This type of file can easily be converted to *.stl for printing using free software that manipulates point cloud data files.



Alignment: Free
☐ Contact Pair Selection
☐ Use Texture 99
Fusion
Resolution 4000
--> Vertex Spacing: 0.225 mm
Refinement ☑
Close Holes ☐

List of Scans:
Scan_01.obj
Scan_02.obj
Scan_03.obj
Scan_04.obj
Scan_05.obj
Scan_06.obj
Scan_08.obj
Scan_09.obj

Working Directory: C:\Users\mcaliste\Documents\Craig
FusionResult.obj
FusionResultto be fixed.obj
Scan_01.obj
Scan_02.obj
Scan_03.obj
Scan_04.obj
Scan_05.obj
Scan_06.obj
Scan_07.obj
Scan_08.obj
Scan_09.obj

Figure 5.13. Individual Scans

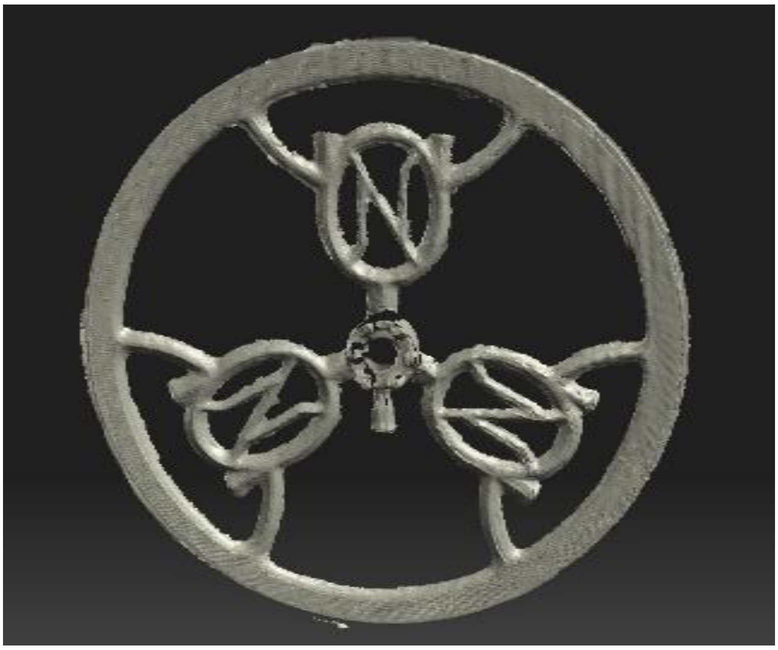


Figure 5.14. Structured Light Scan Data

The major issue with *.stl files is that they are not easily manipulated. There are some software packages including Netfabb, Blendr, Meshlab or FreeCAD that allow *.stl manipulation in varying ways. Mostly, the mesh triangles and point clouds can be manually pushed or pulled on the feature. Scaling and repositioning are common basic practices as well, useful when the file is the wrong scale due to *.stl files being dimensionless and do not translate the correct size unless created in a solid modelling software such as SolidWorks.

An issue which arose was the automatic alignment struggling with the scans of the thin edges and the opposite side of the face shown in Figure 5.14. the edges often did not have enough common popints with the front face of the scan for the software to map exactly where it should go, orientating it completely incorrectly. The opposite side, given the near symmetry of the component being scanned, resulted in its alignment with the first scanned face, instead of continuing the scan from the edges as the scans progressed around the object.

The incomplete scan that was gathered was scaled appropriately using Netfabb and imported into SolidWorks to use as a template to obtain the pulley wheel geometry. Unfortunately, due to the nature of the scans and how they are put together, i.e. the David Laserscanner software automatically stitching the individual scans, small alignment errors are produced which make the model quite rough and not of a high enough quality to be able to produce an accurate model. As with the Sense scan, it would not be capable of producing an identical 1:1 model of the object scanned for reproduction. Chapter 6 further explores this issue and carries out an investigation into the capabilities of the scanners used in terms of their quality of scans.

5.4.5. Phototracing Geometry Collection

Due to the complexity of the other options available and the time it would require to see them through, a simpler option was required. Phototracing is the technique of using a photo to create a 3D model by tracing its 2D outline. This is only possible for parts which have a constant profile as a higher level of complexity would not show all surfaces required for reproduction of the model. This model employs both the tracing of a photograph, but also the traditional method of physical measurement and in this case scaling those measurements as required.

When first taking a photo of the desired object, it is important to take into account perspective distortion. This is an effect which occurs in photography where the image taken is not a true representation of the part photographed. It occurs because the lens of the camera captures the image with a perspective view, rather than as if the object had been scanned. To overcome this effect, the picture needs to be taken as far away as possible which reduces the wide angle distortion of the camera relative to the boundary of the part. Also, the camera lens must be parallel to the photographed object to further reduce the error [40].

With a suitable photograph of the object taken with distortion errors reduced as much as possible, it was then possible to import the drawing into a sketch on SolidWorks on the chosen plane. The picture requires scaling to get it to the required size, thus using the origin, a circle of the desired 320mm diameter is drawn and the picture scaled and positioned to fit into place with the highest level of accuracy possible, shown in Figure 5.15.

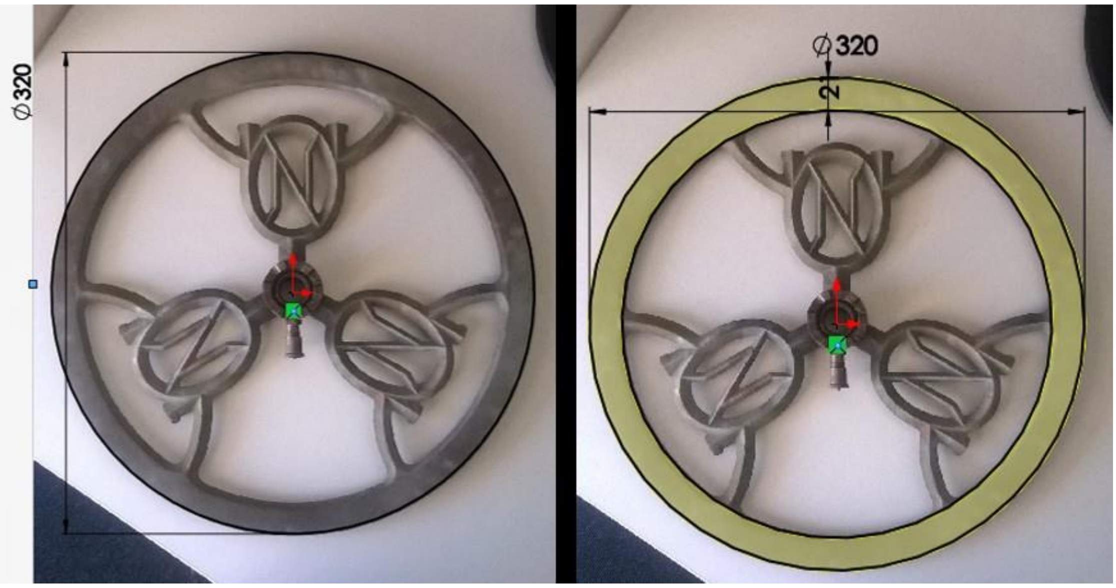


Figure 5.15. Use of Phototracing Technique

The drawing is now to the correct scale for use in recreating the ornate spokes for the smaller Uno pulley wheel and as such this is where the diameter is derived. The original diameter of the pictured pulley is 390mm, thus giving a scaling factor of 0.83 to be applied to any measured thicknesses of the spokes i.e. 15mm original spoke size is now 12.5mm for the new pulley. To validate any sizes calculated, a line drawn over the photograph sketch can be measured to ensure that the spokes are the correct size.

In order to model the spokes with accuracy of the contours and chamfers present in the design, the sweep function in SolidWorks was selected. A simple extrusion of the profile, and then applying chamfers did not yield adequate results as the software could not apply the chamfer function to all faces and when it could, it did so unsymmetrically. The sweep function uses a sketched line as a guide to extrude a profile shape along the length of this rail. By tracing the spokes outline in the photograph and using geometric shapes and straight lines as much as possible, the complex pattern was simplified into sections that could easily be defined. As can be seen in Figure 5.16, the pattern is made from a build-up of numerous simple radius curves and straight lines with angular relationships between them. Using this, separate sketches were created to place the guide rails upon for each individually swept branch of the pattern.

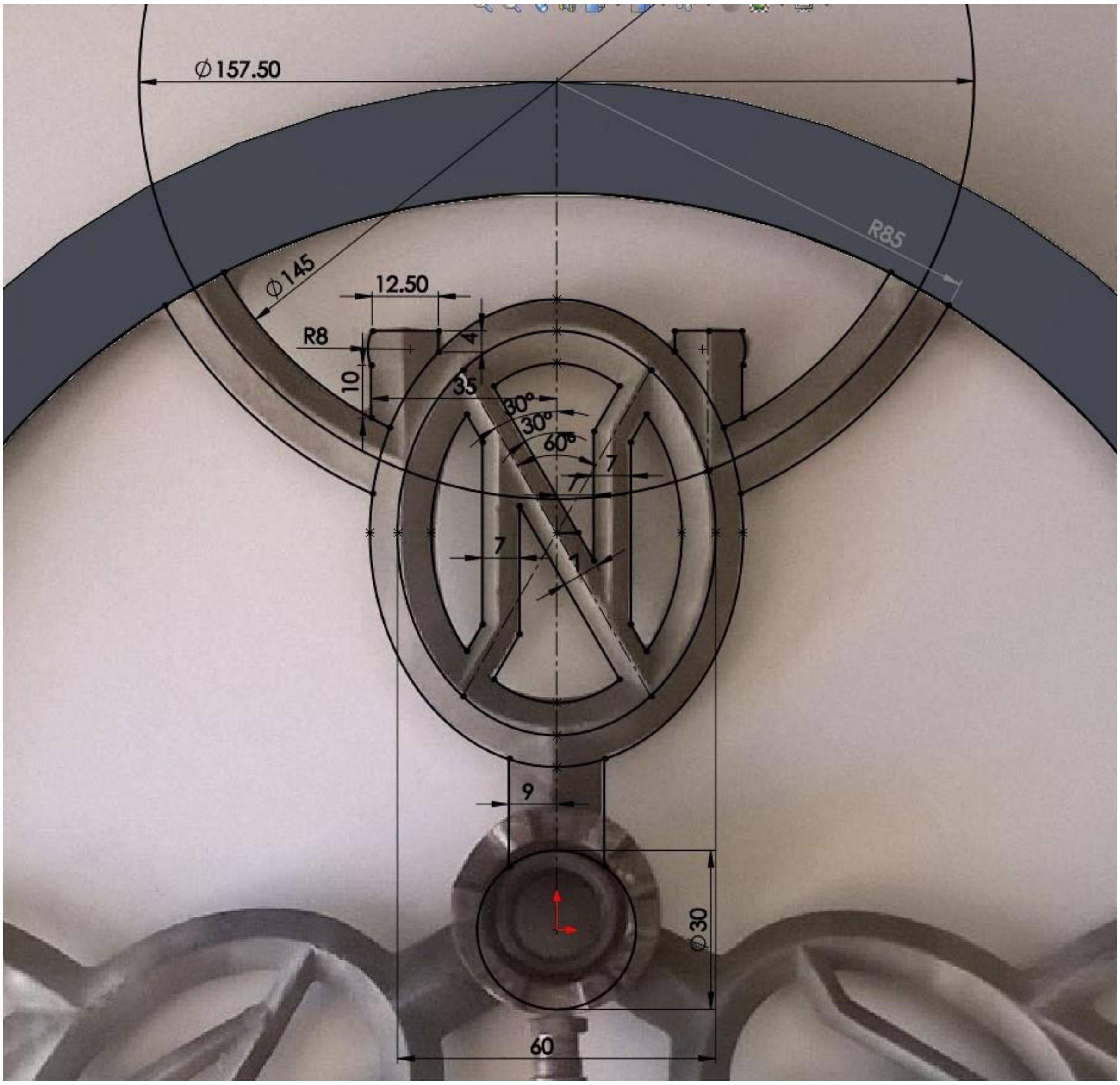


Figure 5.16. Deriving Centreline Relationships for Sweep Function

With the centreline rails for the sweep function calculated, the corresponding profiles for each segment had to be designed. It was calculated that the majority of the sweeps required a profile as labelled (a) in Figure 5.17, whilst the ‘N’ section is represented by the profile (b), and the bottom tab which connects the bottom of the ‘O’ to the central hub is profile (c).

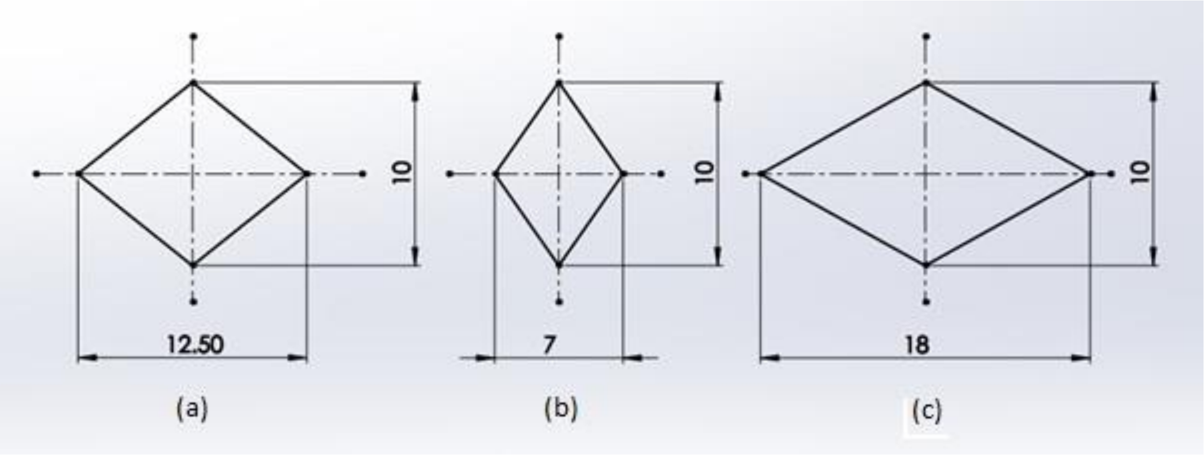


Figure 5.17. Sweep Profiles

With the ornate spoke pattern determined and its individual components realised and modelled, the centre hub could be incorporated into the design as shown in Figure 5.18. As it is to fit onto an existing axle that connects the pulley wheel to the roasting drum, the centre had to fit a 5/8” bar. Also incorporated into the hub is a through hole for a sprung dowel to be inserted, which required the removal of the plate metal pulley that this design is to replace, in order to obtain the correct sizes and maintain pulley alignment.

Figure 5.18. Swept Spokes and Application of Circular Array

Figure 5.19 below shows the resultant model created using the Phototracing technique. From this model, drawings for manufacture can be created (see Appendix 8.2) as well as IGES or Step files which are used for machining processes.

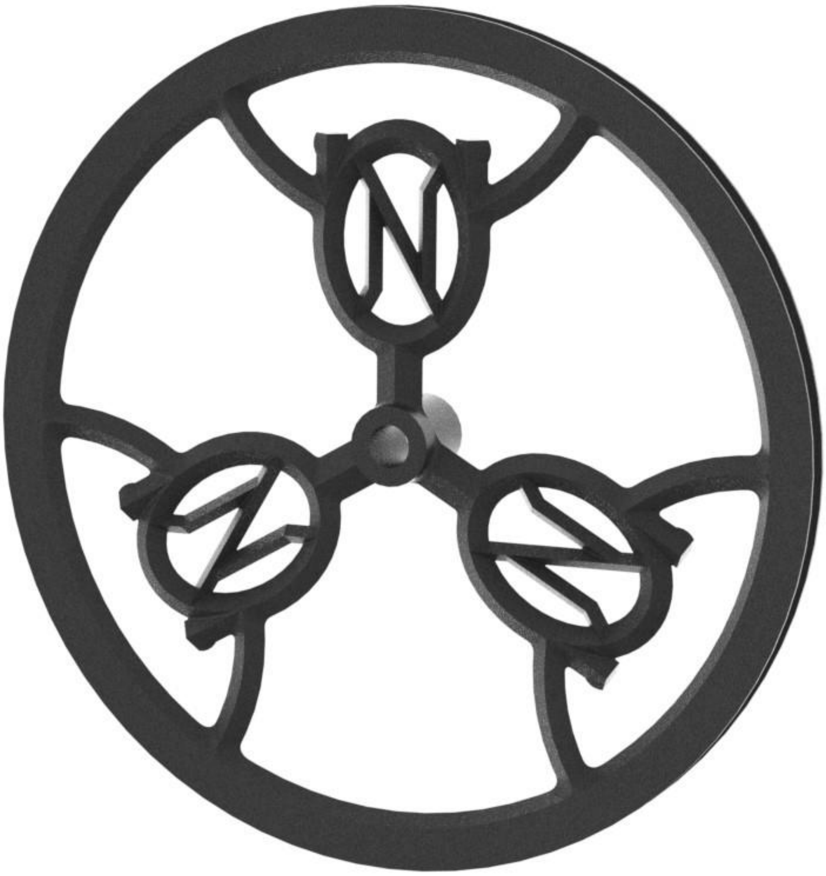


Figure 5.19. Uno Drum Pulley Wheel

5.4.6. Finite Element Analysis

Once the CAD model is produced, CAE can be employed to ensure that the design is capable of performing in its intended use. Finite Element Analysis (FEA) was used to predict the stresses that the pulley wheel will undergo during operation. This is an important step because the part which was designed and modelled using the reverse engineering approach will not be an exact replica of the original part, given that there was no way to tell its exact geometry. Being able to simulate the loading that it will undergo can ensure that the newly designed component will not fail.

The largest stress that the pulley will undergo, is upon its acceleration to operating speed. Theoretically it takes no torque to rotate a drum, so long as it starts turning from equilibrium and is a symmetrical geometry, though in actuality there is friction resistance from the bearings upon which it is mounted. In the case of the Uno, there are small parts such as the hatch on the drum which makes it asymmetrical. Although for the purpose of simplification, this will be ignored.

However, when the drum is full of coffee beans, there is a mass of 7lbs (3.175kg), the maximum mass of beans the machine is capable of roasting, which must be overcome when the drum begins to rotate. The motor is stated as having a speed of 1420 rpm (Figure 5.20).

Figure 5.20. Uno Coffee Roaster Motor Specifications

The rotational speed (N) at each wheel can be calculated by using the ratio of the diameters (D) [41]:

$$\frac{N_1}{N_2} = \frac{D_2}{D_1} \qquad \text{[Eq.1]}$$

For example:

$$N_2 = \frac{D_1 \times N_1}{D_2} = \frac{4 \times 1420}{14} = 379\, rpm \qquad \text{[Eq.2]}$$

Using this method, the rotational speed of D4 can be calculated as shown in Figure 5.21.

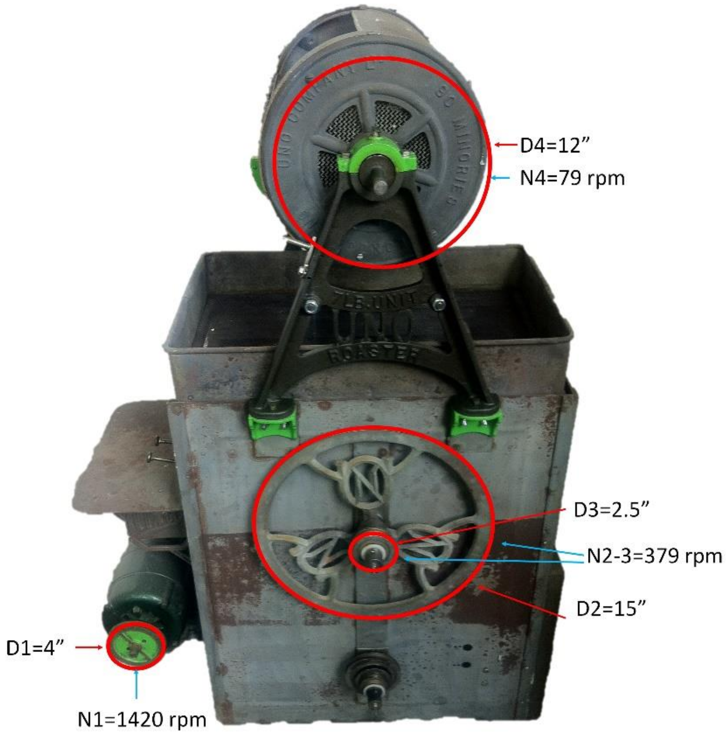


Figure 5.21. Uno Pulley Rotation Speeds and Dimensions

To simplify any equation to be carried out, the FEA will focus on the stresses as a result of the torque produced when the machine is turned on and the drum is turned to full speed from a standstill. There are other forces acting upon the wheel, such as the belt tension between the two pulleys, though compared to the forces needed to turn the drum it is small enough to be disregarded. The torque can be calculated using Equation 3 [42]:

$$\tau = I\alpha \qquad \text{[Eq. 3]}$$

Where:

τ is torque (N/m)

I is moment of inertia $= mr^2\ (kg/m^2)$ [Eq. 4]

α is angular acceleration $= \frac{d\omega}{dt}\ (rad/s^2)$ [Eq. 5]

m is mass (kg)

r is the distance of the mass from the rotational axis (m)

ω is angular velocity $= N\ (rpm) \times \frac{2\pi}{60} (rad/s)$ [Eq. 6]

t is the time of acceleration (s)

Using the equations above, and the information given below, calculations can be done to find the torque to be applied to the pulley wheel:

Known Factors:

$t = 0.5s$

$m = 7lbs = 3.175\ kg$

$r = 0.2m$

$N = 79\ rpm$

Calculations:

Applying [Eq. 6]: $\omega = 79 \times \frac{2\pi}{60} = 8.273\ rad/s$

Applying [Eq. 5]: $\alpha = \frac{8.273}{0.5} = 16.546\ rad/s^2$

Applying [Eq. 4]: $I = 3.175 \times 0.2^2 = 0.127\ kg/m^2$

Applying [Eq. 3]: $\tau = 0.127 \times 16.546 = \mathbf{2.1\ Nm}$

Ansys Methodology

With the rotational force determined, the Solidworks model of the Uno pulley wheel was imported into Ansys workbench, a FEA software. The model was linked to the geometry input for a static structural analysis (Figure 5.22).

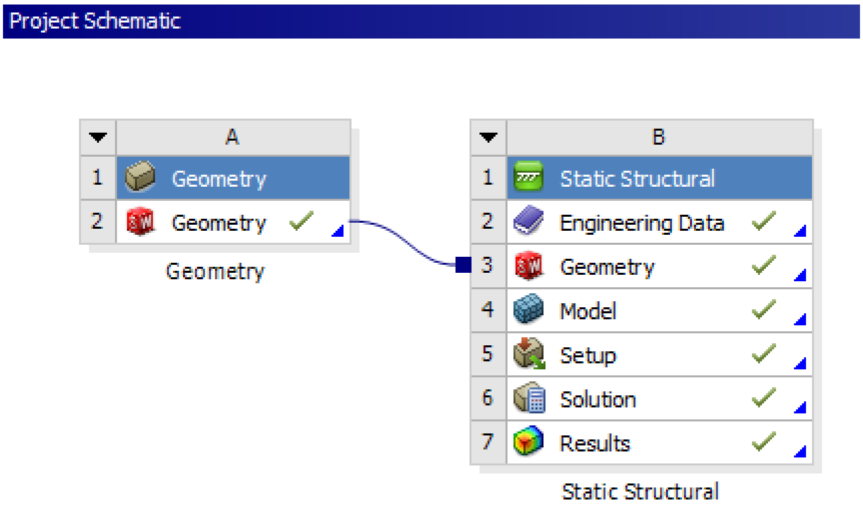
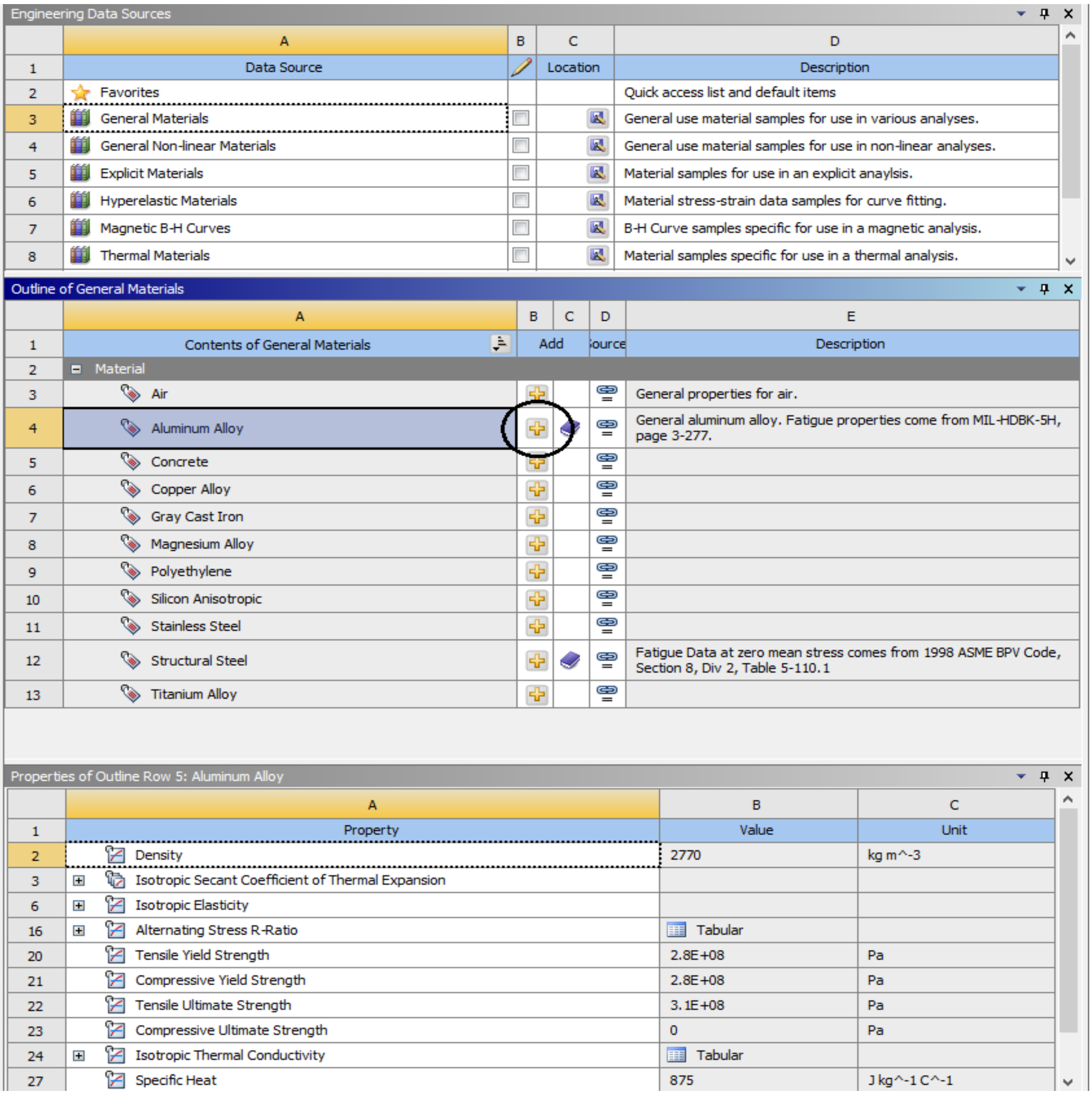


Figure 5.22. Ansys Project Schematic - Imported Solidworks Model and Static Structural Analysis

The Engineering Data tab contains the material information to be used on the geometry. It is set to structural steel as default so this must be changed to aluminium alloy by selecting the appropriate material and it accompanying properties from the engineering data sources and adding it to the data tab (Figure 5.23).



Engineering Data Sources

	A	B	C	D
1	Data Source		Location	Description
2	Favorites			Quick access list and default items
3	General Materials	☐		General use material samples for use in various analyses.
4	General Non-linear Materials	☐		General use material samples for use in non-linear analyses.
5	Explicit Materials	☐		Material samples for use in an explicit anaylsis.
6	Hyperelastic Materials	☐		Material stress-strain data samples for curve fitting.
7	Magnetic B-H Curves	☐		B-H Curve samples specific for use in a magnetic analysis.
8	Thermal Materials	☐		Material samples specific for use in a thermal analysis.

Outline of General Materials

	A	B	C	D	E
1	Contents of General Materials	Add		ource	Description
2	Material				
3	Air				General properties for air.
4	Aluminum Alloy				General aluminum alloy. Fatigue properties come from MIL-HDBK-5H, page 3-277.
5	Concrete				
6	Copper Alloy				
7	Gray Cast Iron				
8	Magnesium Alloy				
9	Polyethylene				
10	Silicon Anisotropic				
11	Stainless Steel				
12	Structural Steel				Fatigue Data at zero mean stress comes from 1998 ASME BPV Code, Section 8, Div 2, Table 5-110.1
13	Titanium Alloy				

Properties of Outline Row 5: Aluminum Alloy

	A	B	C
1	Property	Value	Unit
2	Density	2770	kg m^-3
3	Isotropic Secant Coefficient of Thermal Expansion		
6	Isotropic Elasticity		
16	Alternating Stress R-Ratio	Tabular	
20	Tensile Yield Strength	2.8E+08	Pa
21	Compressive Yield Strength	2.8E+08	Pa
22	Tensile Ultimate Strength	3.1E+08	Pa
23	Compressive Ultimate Strength	0	Pa
24	Isotropic Thermal Conductivity	Tabular	
27	Specific Heat	875	J kg^-1 C^-1

Figure 5.23. General Aluminium Alloy Properties; Adding to Engineering Data Tab

Once the material has been added, the model tab can be opened, which allows the setup and solution parameters to be set and results to be generated. The material can be selected from the parts 'material assignment' under the 'geometry' tab. As the aluminium alloy was added previously, it can now be assigned to the part. The geometry must then have a mesh applied to it. This is made up of a number of triangles which spilt the part into sections for the software to analyse each individual section (Figure 5.24). The finer the mesh, the more accurate the results will be as the geometry has been more thoroughly analysed. However, the more elements there are in a mesh, the longer it will take the software to compute any loading effects that are applied.

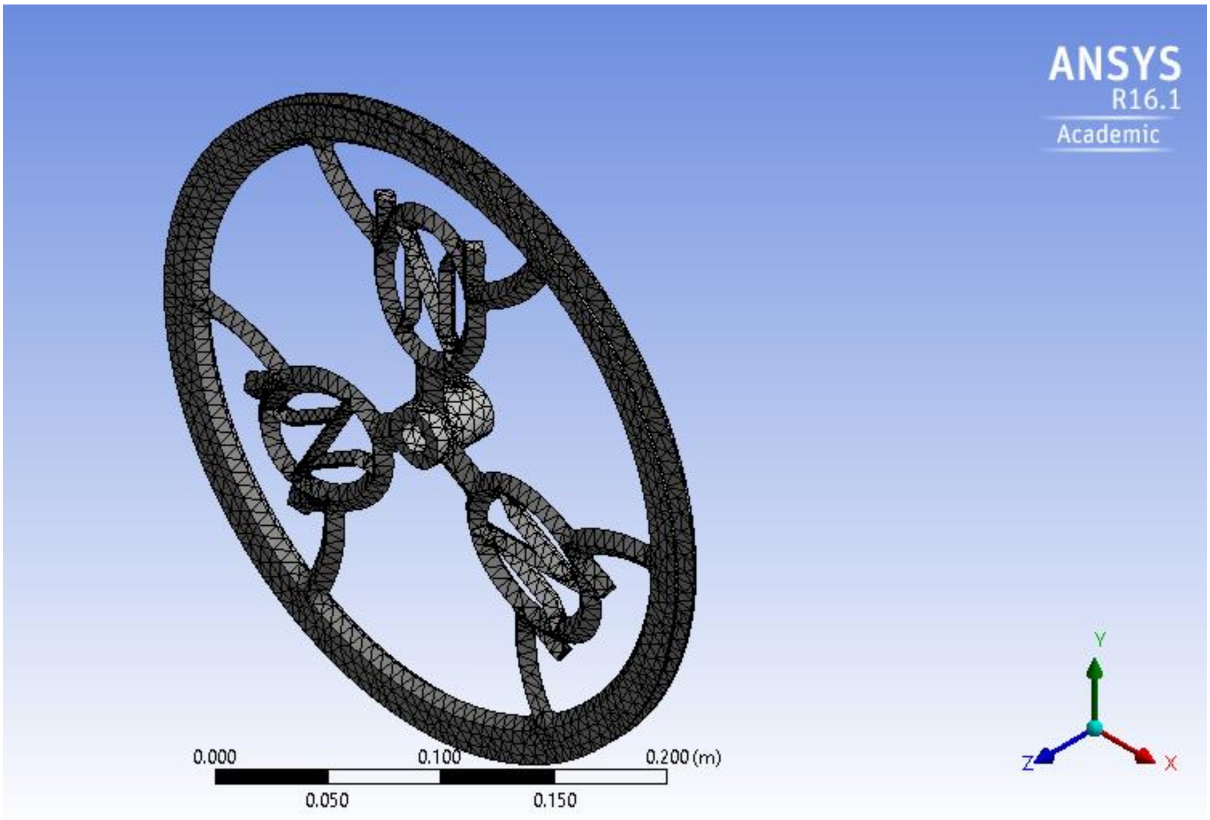


Figure 5.24. Ansys Uno Pulley Wheel Geometry Meshing

Once a suitable mesh has been created, the setup of the static structural can continue with introducing supports and loadings to the geometry. A fixed support was added to the centre bore of the shaft (Figure 5.25), and a moment was applied to the v-belt profile. The torque of 2.1Nm that was calculated beforehand was used as the moment, and rotates around the z axis (Figure 5.26).

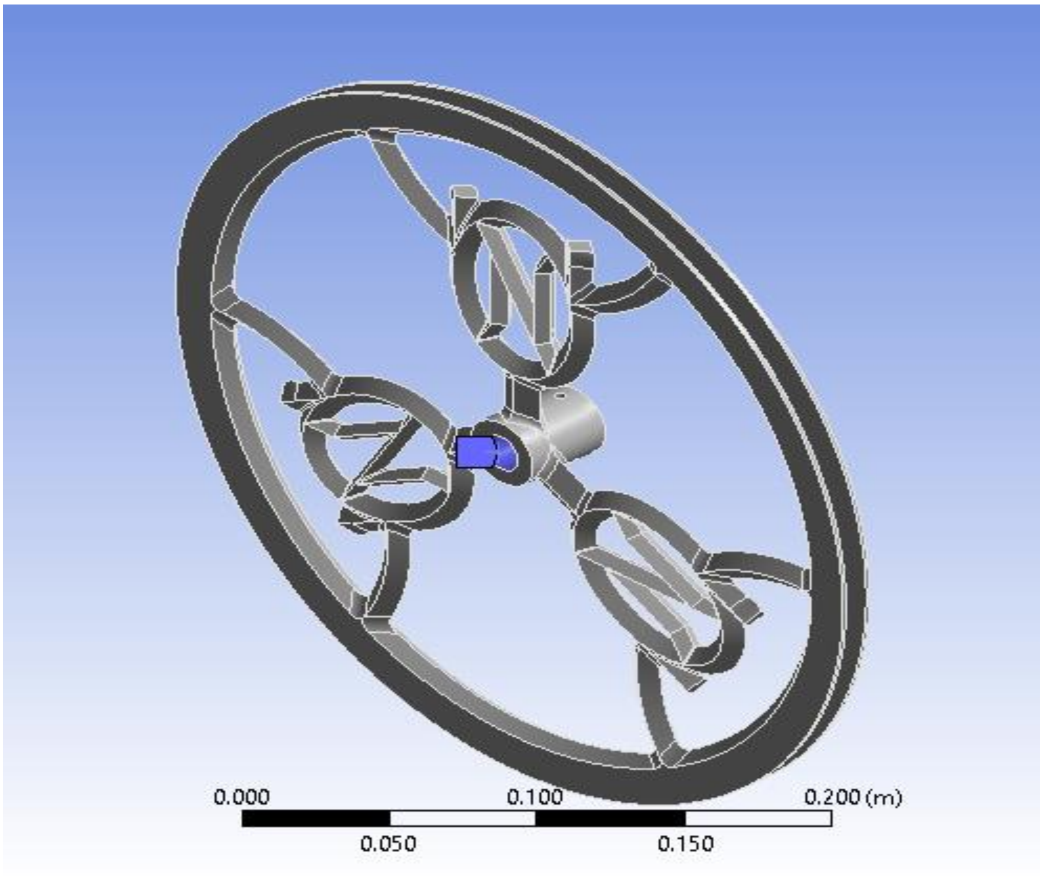


Figure 5.25. Ansys Fixed Support

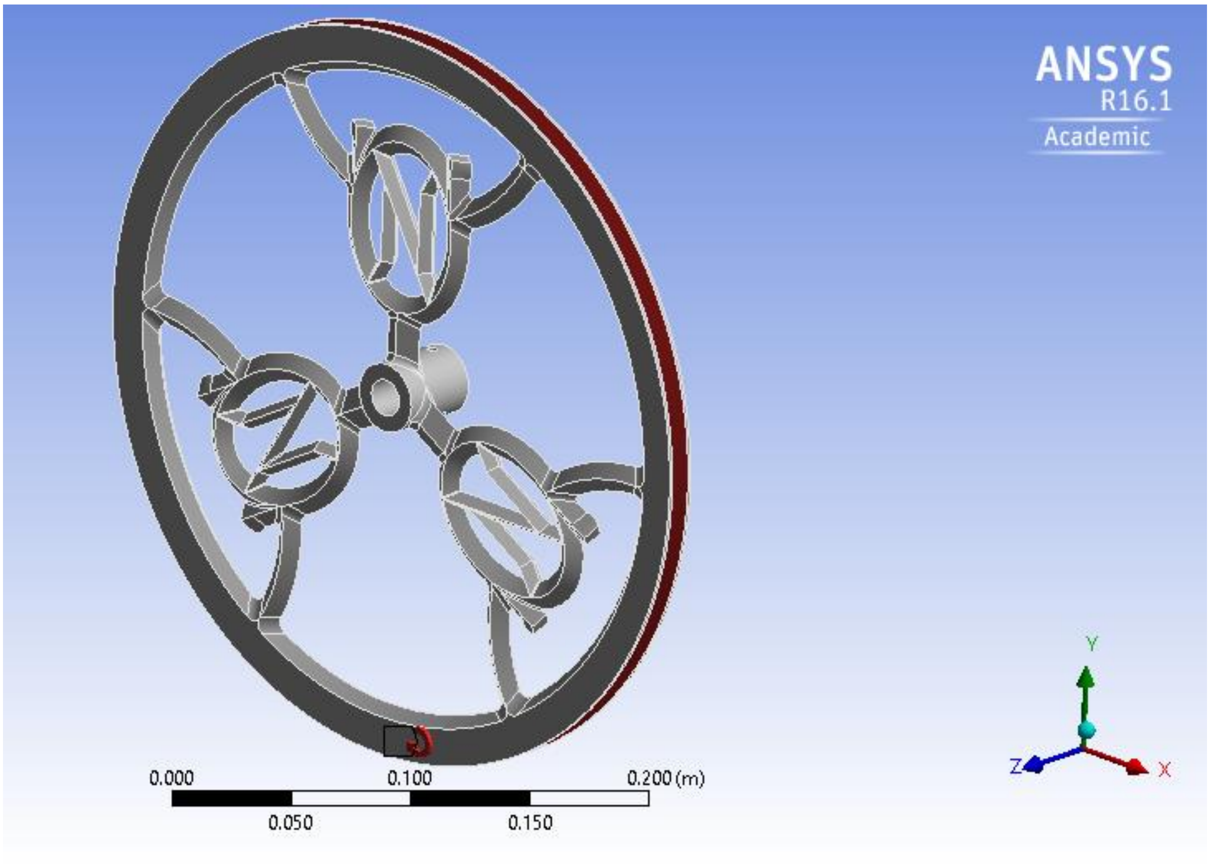


Figure 5.26. Ansys Moment of 2.1 Nm around Z-Axis

With the input s of the setup determined, the outputs must be selected. In this case the maximum stress present on the pulley wheel upon initial rotation of the coffee drum was defined (Figure 5.27). Thus equivalent stress was selected from the options. Other options are available which give more of a breakdown of stresses such as the maximum, middle and minimum principal stresses, though the selected option will give the largest combined stresses. Other possible outputs are strain and deformation, though these are not required in this analysis.

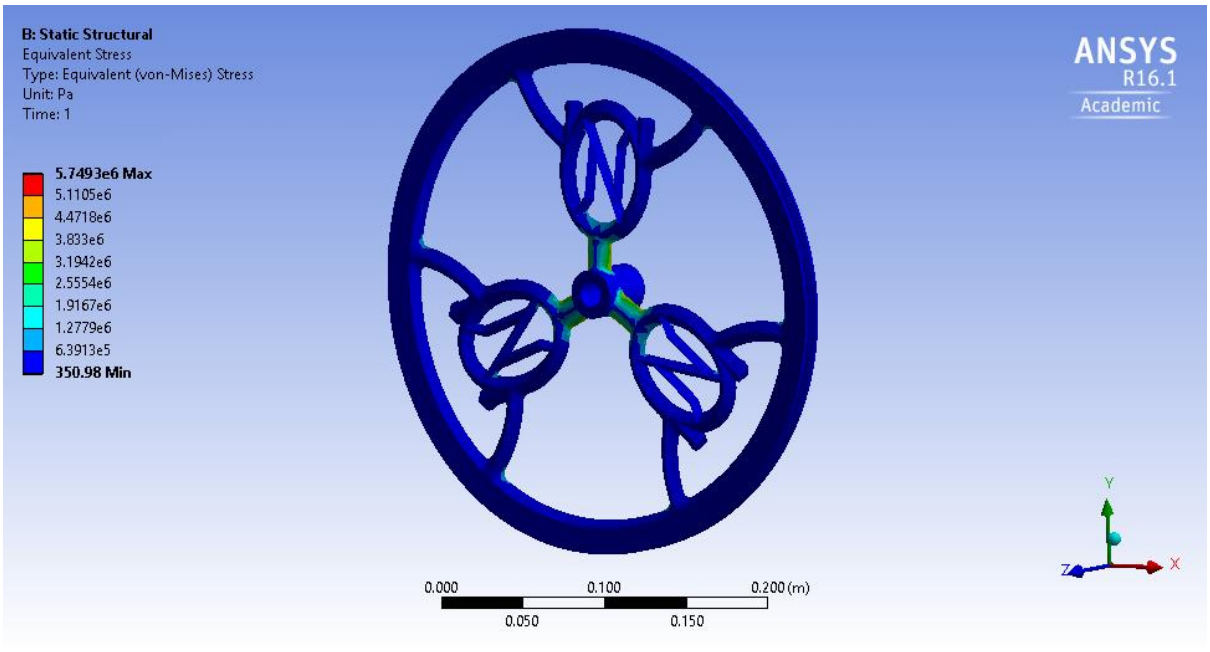


Figure 5.27. Ansys Equivalent Stresses acting upon Uno Pulley Wheel

As can be seen from the figure above, the greatest stress that the pulley will experience is 5.7493 MPa. It is concentrated round the base of the spokes as shown in Figure 5.28. The yield strength of the general aluminium alloy is 280 MPa so the comparable strength of the material compared to any stresses present on it is far greater. Thus, even if a combination of any other loading will result in a higher stress it is unlikely that it will cause any issues. Likely sources of additional loading could come from frictional resistance form the bearing which support the drum, thus increasing the amount of force required to start it turning. As well as any forces which keep the belt tight between the pulleys. It is safe to assume that the design of the Uno pulley wheel will safety withstand any loading conditions it will be presented with.

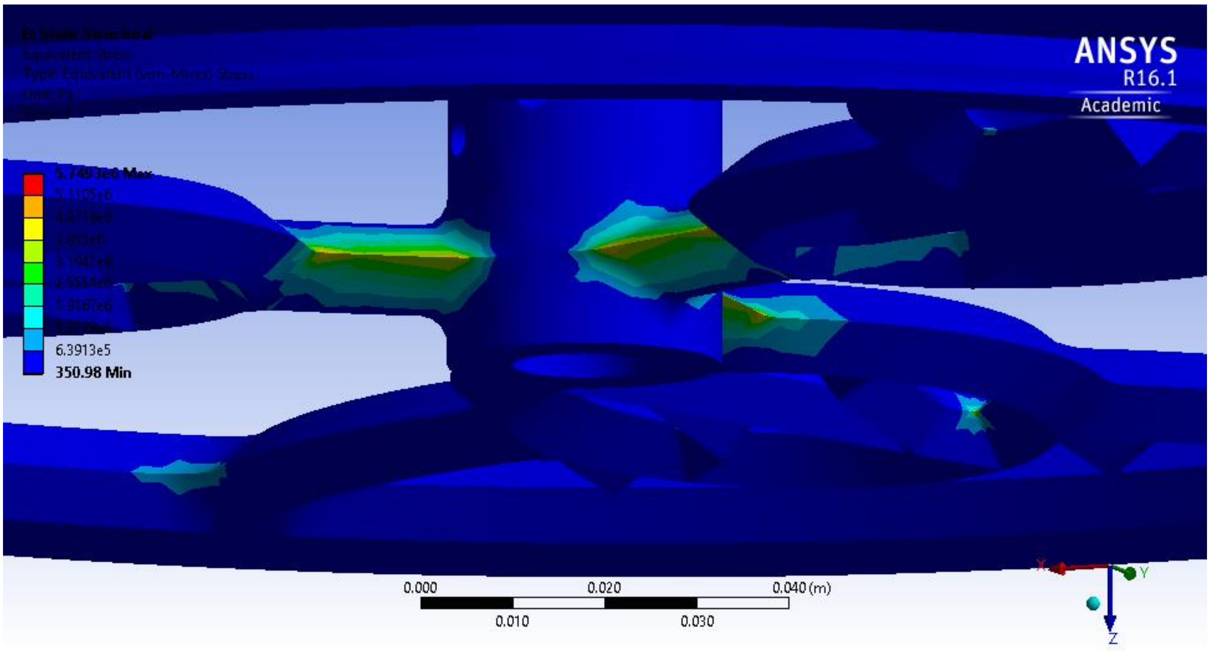


Figure 5.28. Maximum Stress Area on Pulley Wheel Spokes

5.4.7. Manufacturing Options

There are numerous options and processes available to realise the CAD model of the Uno pulley wheel. As discussed previously (Chapter 4.2.1.), the original method of manufacture of this part would have been to fabricate a pattern from wood, then use it as a sandcasting mould. This option will be explored with a modern manufacturing method incorporated into the traditional method.

Currently, patterns for sandcasting are produced by means of either manual fabrication or computer aided fabrication. Figure 5.29 below shows the process steps for pattern fabrications along with the options available for each method. With manual fabrication, the pattern is typically made from wood, clay or plastic and it is hand made by a patternmaker or skilled worker.

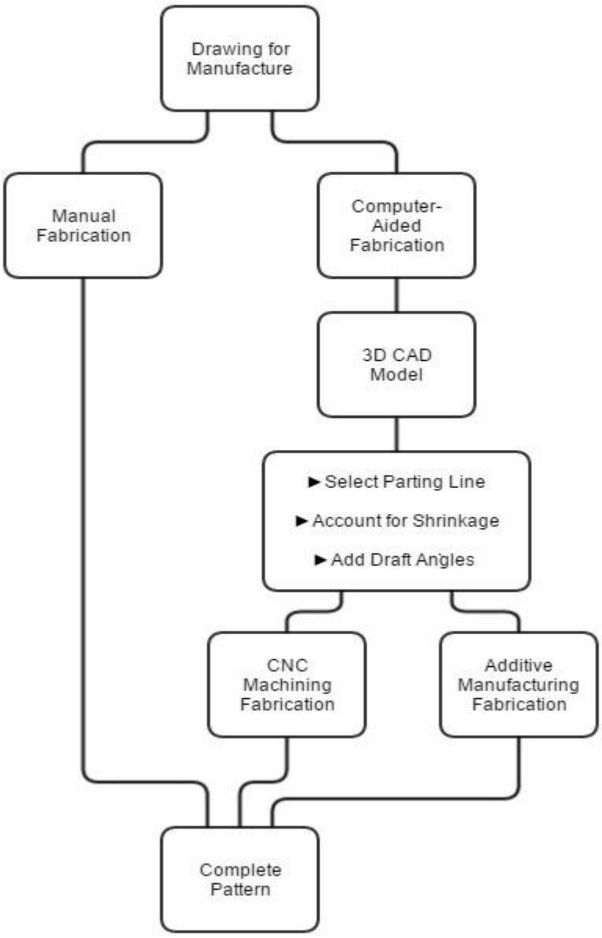


Figure 5.29. Pattern Fabrication Process for Sand Casting

With regards to computer aided fabrication, a 3D computer model must first be created to replicate the pattern desired. This includes incorporating draft angles and considering shrinkage as the part cools as well as selecting the most appropriate position for the parting line. Once the model is complete it can be used in two ways to manufacture the pattern; either by the use of automatic manufacturing techniques such as CNC machining or through the use of AM processes.

Any imperfections are passed on to the mould and thus the final cast part, so they must be accurate.

5.5. Uno Pulley Wheel Sand Casting

5.5.1. AM Pattern

The pulley wheel for the roasting drum was originally manufactured by casting and is ideal to test the use of AM techniques to create patterns for sand casting. Sand casting was picked against other casting techniques as it is one of the least difficult methods, with few process steps, and the materials it requires are readily available and inexpensive. From the 3D model created in SolidWorks, as discussed in Chapter 6.2.2, an altered model can be made for printing.

The SolidWorks model was modified to make it more suitable for sandcasting. Draft angles were added to the core shaft and to the outer rim once the v-belt profile was removed. The belt profile would cause an undercut which requires a core in order to make it, thus machining the profile into the cast part is an easier course of action. The gating system was incorporated into the model to make the forming of the mould easier and more precise, in theory. Traditionally, when sand casting, the gating system is created by gluing material to the pattern, or by sculpting the sand once the cavity is formed by the pattern. By manufacturing the gating system into the pattern, it reduces steps in the manufacturing process as well as increasing the precision in the placement of runners and risers. However, this presents its own problems, as the pattern still needs to be able to release from the mould. To accomplish this, draft angles were applied to the risers, which can be seen in Figure 5.30. To ensure the pattern would separate from the mould, the pouring cup and downsprue were modelled as an individual part which joined to the pattern by use of the hole in the shaft as demonstrated in Figure 5.31. This allows the pouring cup to be removed once the cavity is formed and for the main pattern to be ejected. Once the model was completed, it was split along the parting plane to create two separate halves of the pattern. With the pattern being halved, as shown in Figure 5.32, it provides a flat base on each half from which they can be printed as well as ensuring that the pattern split is aligned with the cope and drag parting plane, which will be discussed later in this chapter.

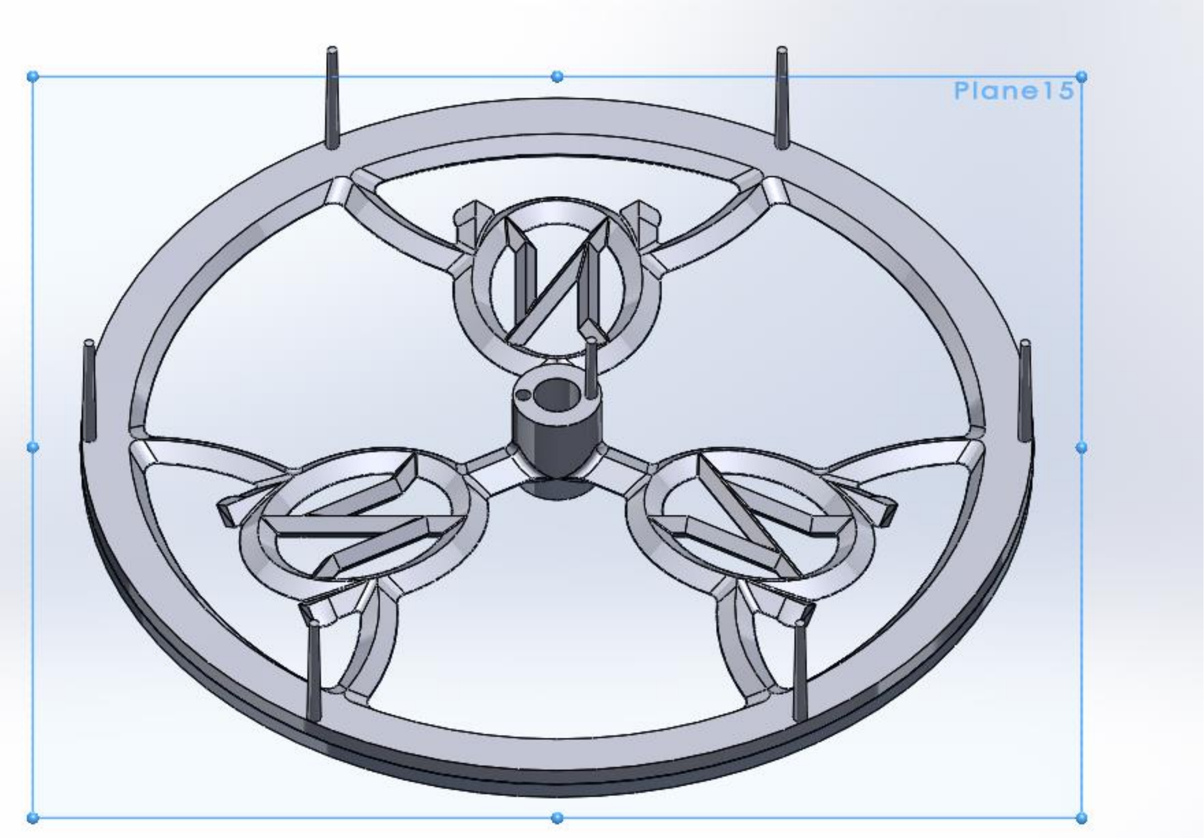


Figure 5.30. Pattern SolidWorks Model

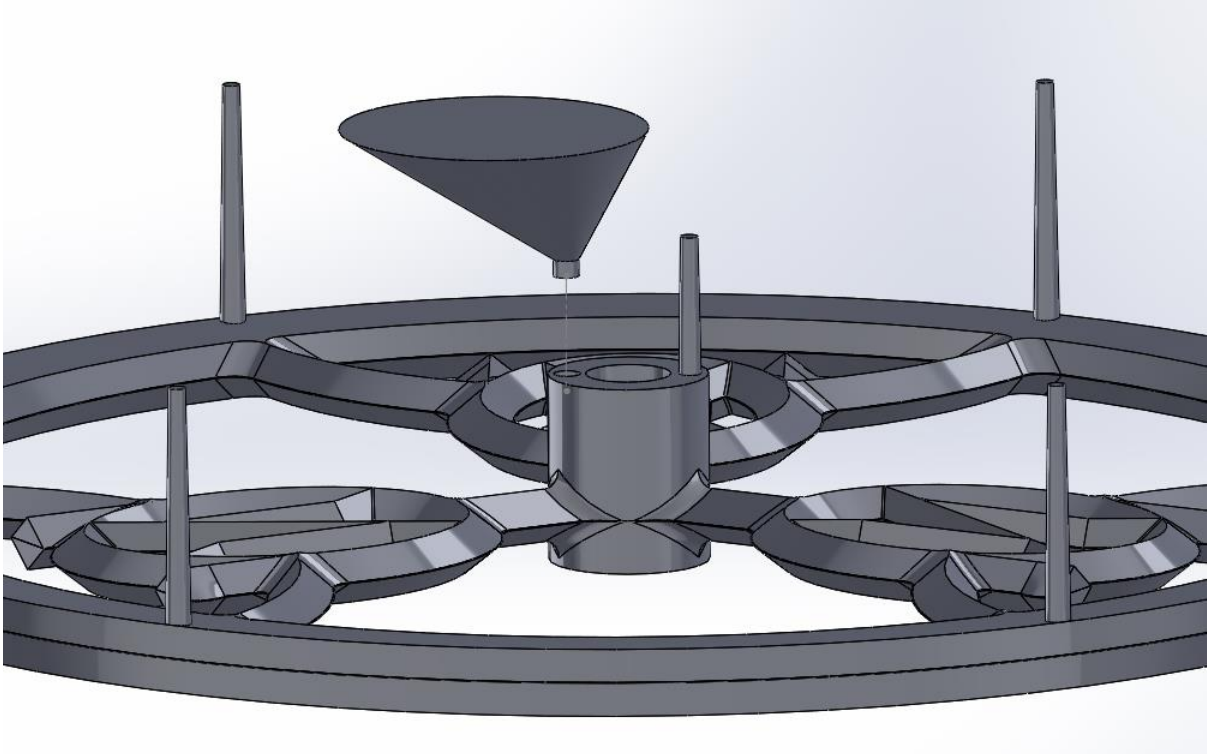


Figure 5.31. Pouring Cup and Downsprue Alignment for Pattern

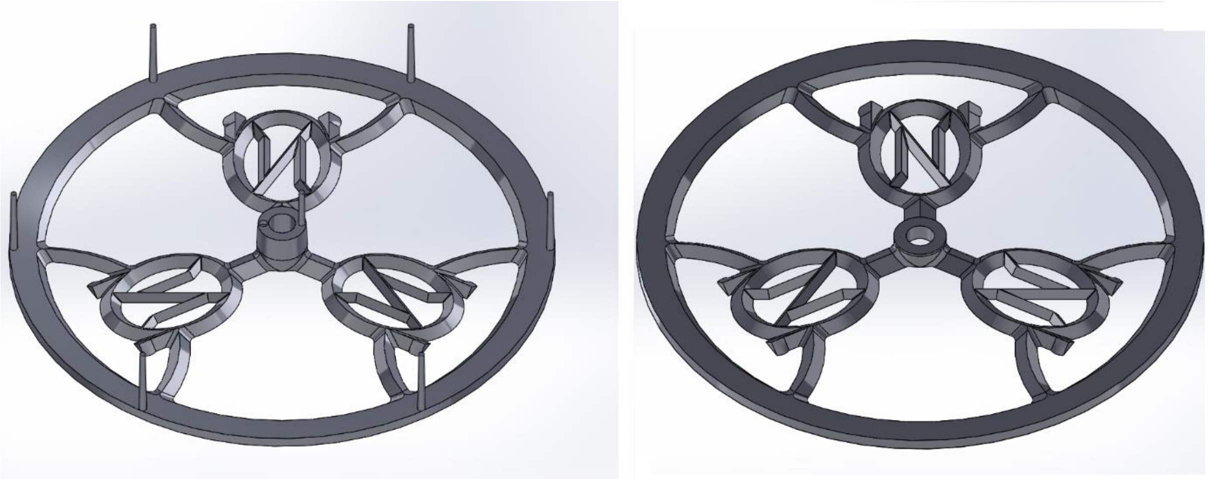


Figure 5.32. Cope (Left) with Gating System and Drag (Right) Patterns SolidWorks Models

The model had to be scaled down by two thirds, giving it a 200mm diameter. This was so that it would fit on the build platform of the AM machine chosen to build the pattern. A FDM machine was selected to build the pattern, as can be seen in Figure

5.33. FDM was used as opposed to SL or SLS, which were the other options available. SLS would have produced the parts, but there is a high probability that the parts would warp due to heat sinks in the build area. While FDM also suffers from this issue, it is much more difficult to correct on an SLS and requires compensation for the sintered powder contracting when cooling [43]. The finish on a SLS part is a rough and porous, which is not ideal for sandcasting as the sand would adhere to the surface, making pattern removal difficult. The SL machine available in the department was too small to print even the scaled down model, as well as being more expensive in terms of raw material cost. The costing of the available methods is discussed in Chapter 6.5. FDM was the best choice as it provides an accurately dimensioned part, though it does not result in the best surface finish, as would be achievable with SL, but it is more suited than SLS. While the surface finish for FDM is quite smooth, it still has striations from where each layer of the print has been deposited. This is not an issue for sandcasting as the parts traditionally created using this method are expected to have a roughness caused by the impression of the sand itself.

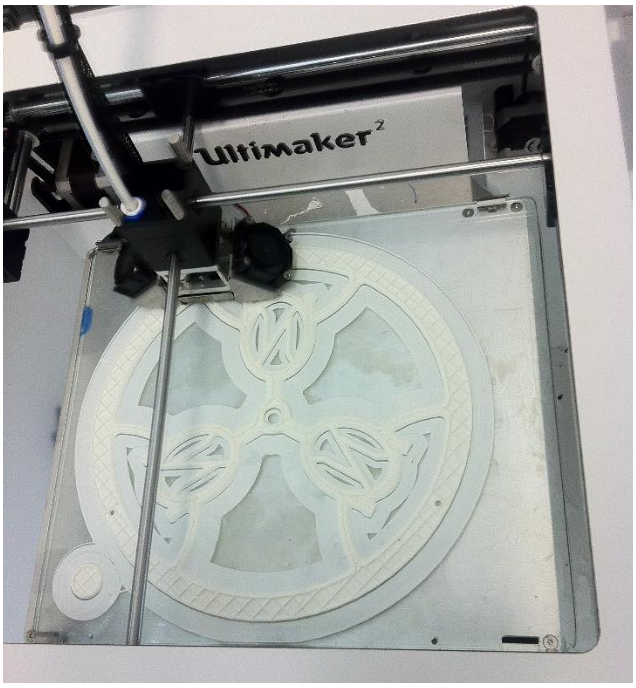


Figure 5.33. Printing Sandcasting Pattern on Ultimaker2 FDM Machine

The results of the prints are shown in Figure 5.34. A combination of the force applied to remove the part from the print bed, and the inherent thermal stresses from printing resulted in the cope half of the part becoming warped. This can be seen in Figure 5.35, where the part does not lie perfectly flat, such as the drag pattern does. Another issue which can be seen in Figure 5.34, is that the risers that were printed onto the cope pattern, have not printed well and are rough and have stringy strands of plastic coming from them. This is not ideal for part removal form the formed mould cavity.

Figure 5.34. PLA Cope (Left) with Gating System and Drag (Right) 3D Printed Sandcasting Patterns

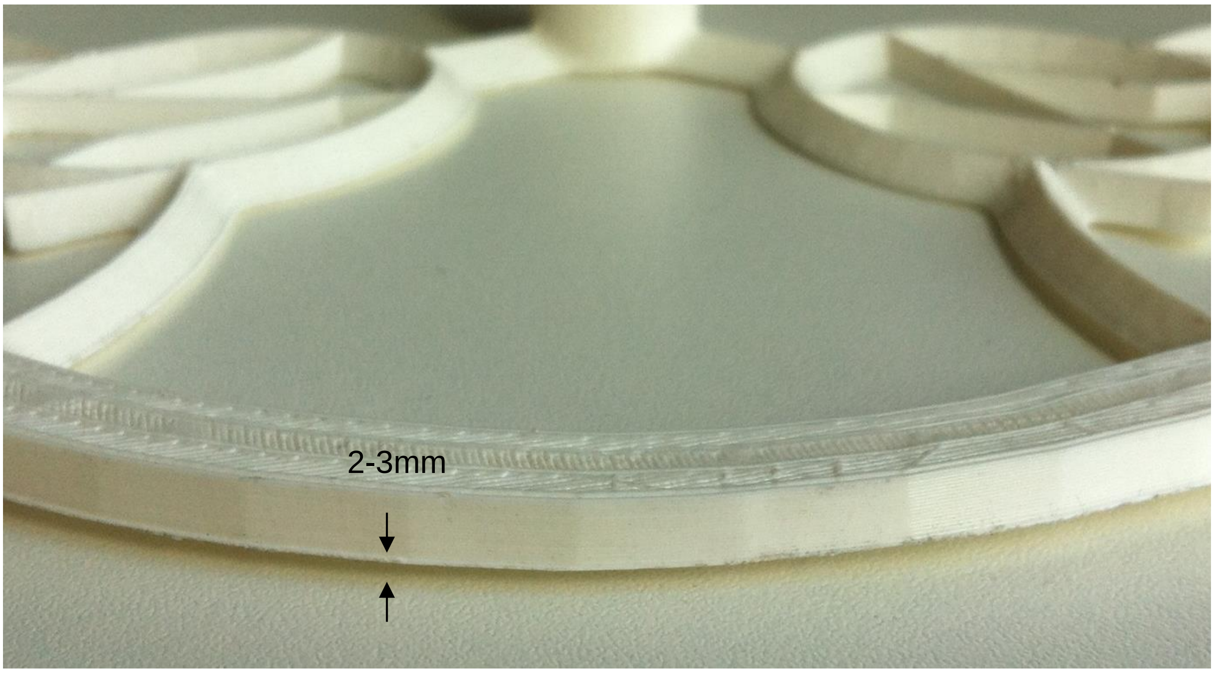


Figure 5.35. FDM Cope Pattern Warping

Polylactic acid (PLA) was selected to print the parts because it is easy to extrude, though is prone to deformation because of the heat [44]. The warped cope pattern was not usable as it would not align properly with its other half, so it required a reprint. To avoid any warping from this print, Acrylonitrile Butadiene Styrene (ABS) was used instead of PLA. ABS is a stronger material, and though it is more difficult to extrude, it is far less likely to warp given its higher stiffness. It does however require a heated print bed to ensure it doesn’t deform [44].

The original cope model was redesigned to account for the failings of the first print. The risers were removed from the model and instead holes were substituted in their place, shown in Figure 5.36. This allowed stainless steel rods to be attached to the pattern, giving a design that was more reliable and easier to remove.

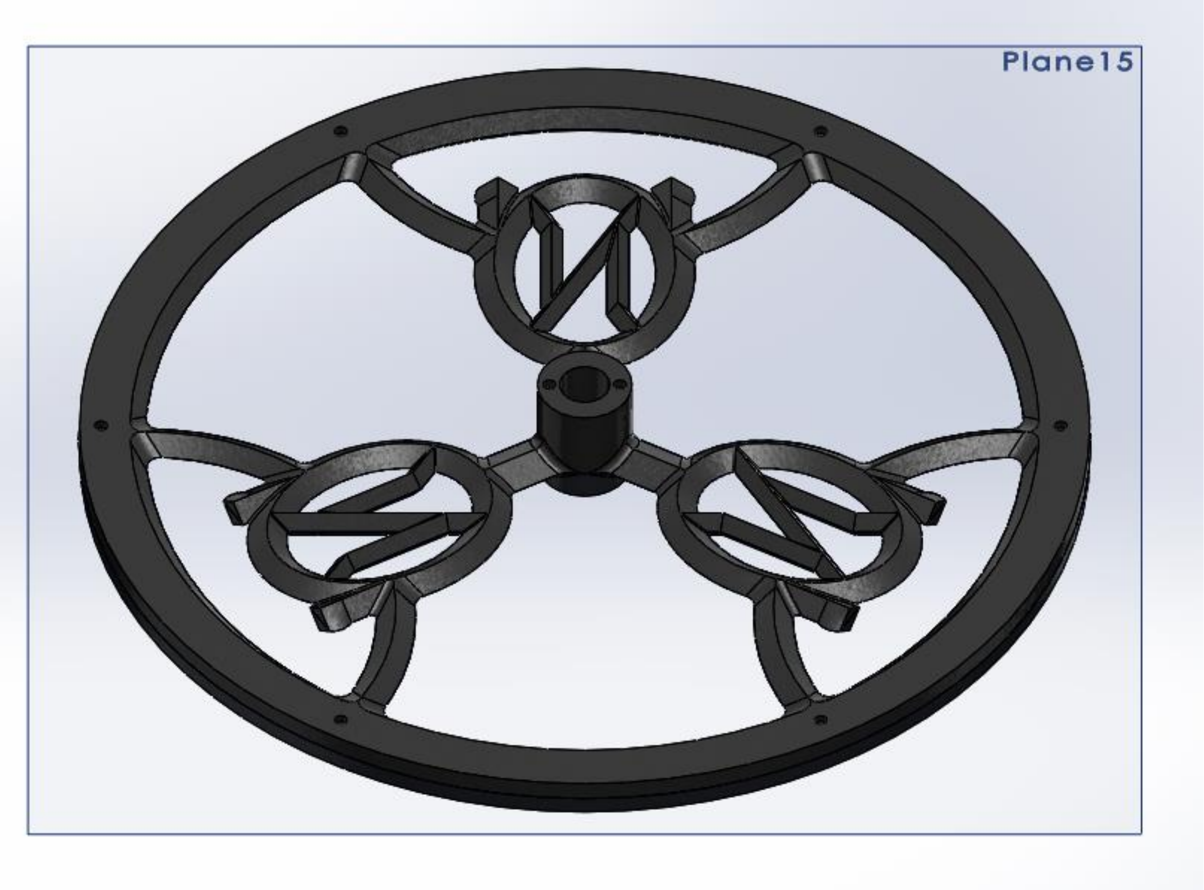


Figure 5.36. Pattern Reprint SolidWorks Model

5.5.2. Casting Process

When sandcasting, it is crucial to align the parting plane of the cope and drag, with the corresponding parting plane of the pattern. In the case of the Uno pulley wheel, its geometry was ideal for being split in half, thus the parting plane had a linear profile, rather than a more complex split line which could have resulted in a non-linear parting plane.

The sand which is used is oil bonded, specifically manufactured for moulding. It binds together under compression and has a high green strength, meaning it can maintain its dimensional and contour accuracy once compacted. It provides a high quality casting surface.

Manufacturing Sandcasting Mould Stages

As can be seen in Figure 5.37 the process for creating the sand mould is shown in 9 steps, explained below.

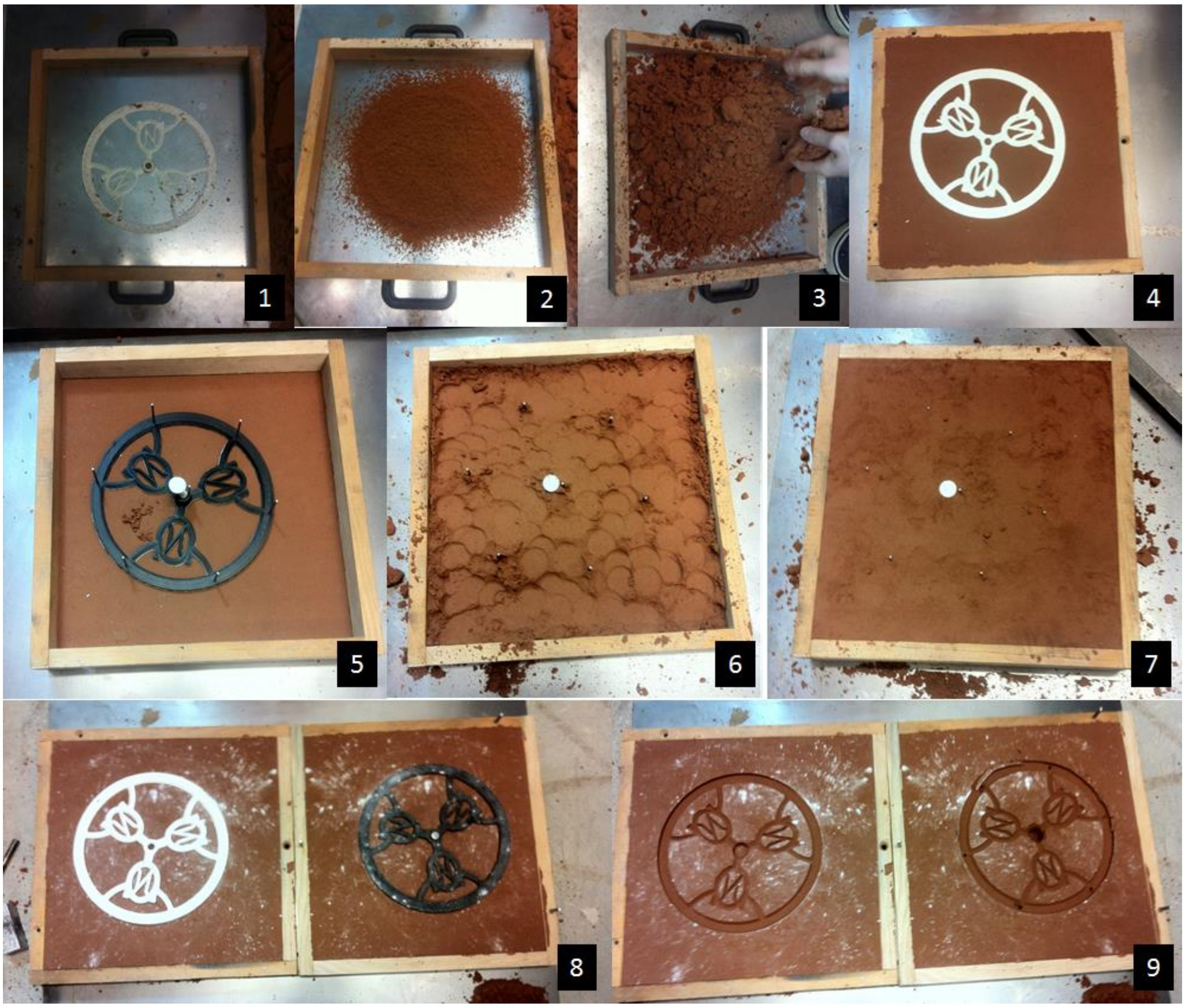


Figure 5.37. Forming Uno Pulley Wheel Sandcasting Cavity Using 3D Printed Pattern

1. The drag and the drag pattern were placed face down, with the parting plane of each part being aligned by a flat surface.
2. To ensure as much fine detail as possible is shown, the pattern is covered completely in sieved sand. This also ensures that no other unwanted particulates are present for direct contact with the pattern, which may yield an unbonded sand cavity. i.e. if a small piece of wood was present, upon removal of the pattern from the cavity, the wood my fall out also, damaging part of the mould.

3. Unseived sand is then broken up and layered onto the pattern, covering the sieved sand and filling in the drag. The sand can then be compressed by use of a hammer or similar device. This is to pack it down and ensure it becomes stiff enough to hold its intended geometry. Steps 3 and 4 are repeated until the sand can no longer be compressed, thus making sure that the pattern will form a tightly compacted cavity.
4. Once the drag is full of compacted sand, it can be turned over and the sand should hold its form if compressed properly.
5. The cope box is fitted to the drag box, and the cope pattern is secured to the drag pattern. A stainless steel rod was used to align the central bores of the shaft. During this stage a parting powder is evenly sprinkled over the sand and pattern to ensure that the pattern will be easily removed and that the sand in the drag will not bond with the sand in the cope.
6. As first described in step 2, sand is sieved onto the pattern covering it completely.
7. Sand can then be piled and compacted multiple times until the cope is full.
8. With both the cope and the drag full of sand, they can now be carefully separated. This will expose the patterns in each half.
9. Each pattern must be removed as carefully as possible to avoid any mould cavity damage. Where cavity damage occurs, typically the mould is fixed by use of moulding tools, used to place and form the sand into the intended geometry for casting.

5.5.3. Sand Casting Attempts

Initial attempts used scrap aluminium obtained in house. The grade of material used was predominantly 6000 series aluminium alloys as is the grade used in the department. This grade of aluminium is not suited for casting, and is typically used for the manufacture of machined products that require high strength, corrosion resistance, hard surfaces and good machinability [45]. It was used to test if it was possible to sandcast the part with any old scrap aluminium available.

Observations

The first sandcasting attempt used the process described in Chapter 6.4.2. An element of difficulty arose when forming the mould cavity on the cope half. The pattern used stainless steel rods to form the risers which made compacting the sand harder than previously with the drag, as can be seen in Figure 5.38. Care had to be taken not to hit the risers as they would break the pattern and not protrude enough from the fully filled cope. The rods were longer than necessary to ensure they protruded from the top of the drag. This served as an ejector pin system when the cope was separated from the drag and laid with the parting plane facing upwards. This ejector pin system was not ideal as it caused the pattern to be pushed out of the cavity unevenly, resulting in damage to the mould as illustrated in Figure 5.39. The damaged areas are concentrated around the outer rim of the pattern as well as the core.

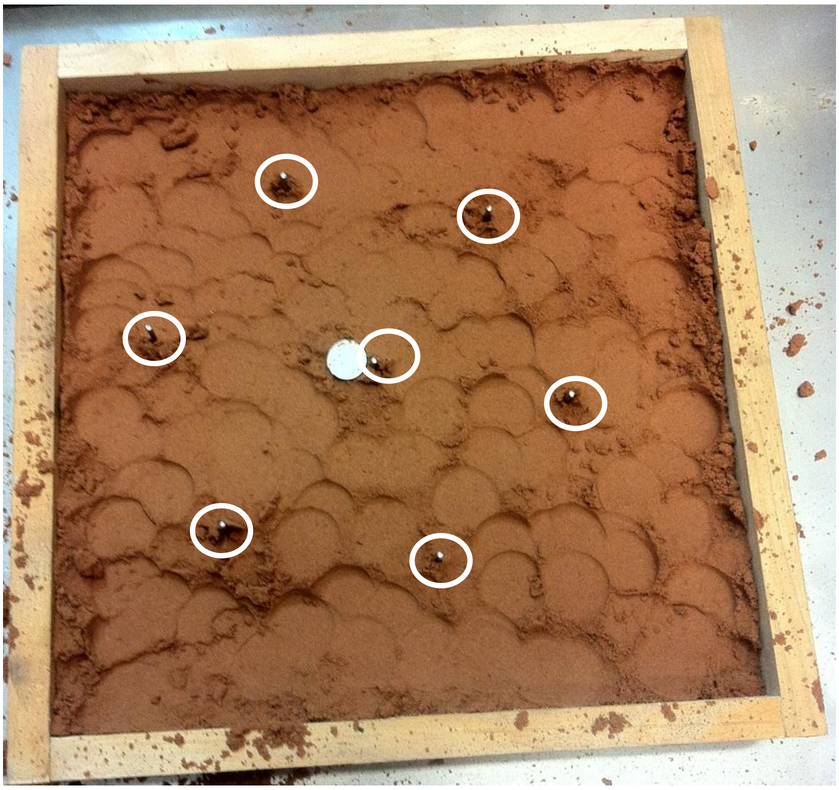


Figure 5.38. Stainless Steel Rod Risers

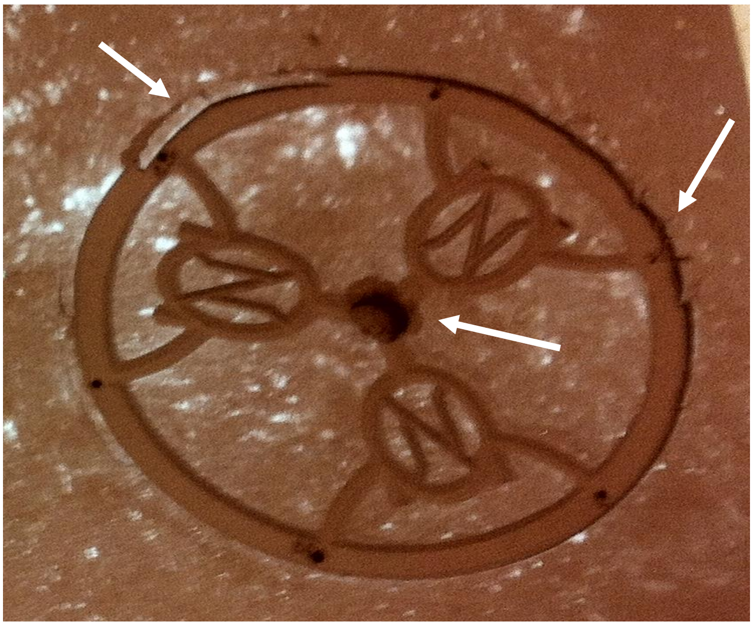


Figure 5.39. Mould Cavity Damage

When forming sand around the pouring cup, a misplaced strike from the hammer caused it to break at the locating pin which inserts to the pattern. Though sand was formed around it and it was aligned with the pattern as needed, this issue had to be addressed for future castings.

The aluminium was heated to 700°C, the typical melting point for 6000 series aluminium being 650°C [45]. Once up to the desired temperature, it was poured in the mould cavity via the pouring cup. The poured part was left to cool and once its temperature had reduced to a safe level, it could be broken out of the mould, shown in Figure 5.40 below.

Figure 5.40. First Sandcast Attempt after Mould Removal

It can be clearly seen from the figure above that a complete casting was not successful. The molten metal did not travel fully along the extents of the pattern cavity. This casting defect is known as a misrun. It can be caused by either the flow of the molten metal being insufficient, a low pouring temperature, too slow of a pour, the cross section of the cavity being too small or a combination of these factors [25].

The shaft of the model also caused issues of cavity destruction upon its removal, as evidenced by the rough features around the base of the spoke, shown in Figure 5.41. This is possibly caused by the sand not being packed densely enough around the area for removal.

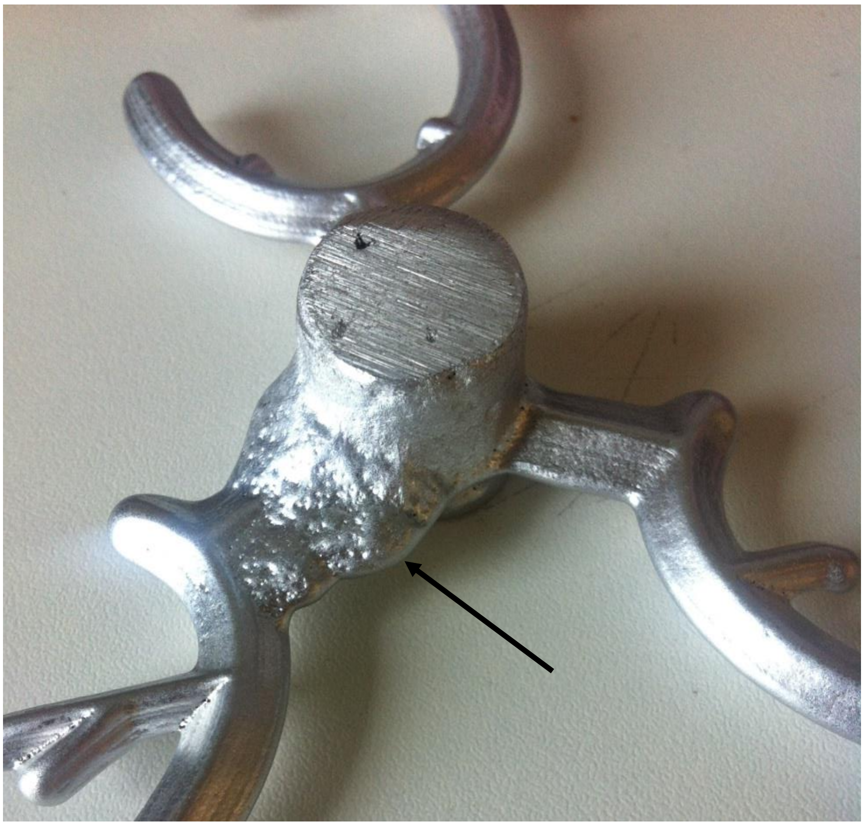


Figure 5.41. Evidence of Cavity Destruction Around Pulley Core

Improved Design Considerations

The casting was incomplete due to the lack of metal flow available to fill the mould. This was caused by the downsprue of the pouring cup solidifying before allowing the required amount of material into the mould. Given its narrow cross section, it is more susceptible to cooling quicker than the rest of the mould, despite the pouring cup directly feeding into it. Figure 5.42 shows where the pouring cup and downsprue are attached to the pattern.

Figure 5.42. Downsprue Cooling due to Dimensional Constraints

To solve the bottlenecking effect the downsprue had on the casting, a redesign of the pouring cup and downsprue was implemented. By extending the central rod which aligns the two halves of the pattern, it could also be used to attach a modified larger pouring cup as shown in Figure 5.43. As before, the part was modelled on SolidWorks, then fabricated on the same FDM machine.

Figure 5.43. Pouring Cup Modification

The design modification of the cup will allow a greater flow rate of molten metal into the mould, and the larger size of the cup will give a larger reservoir supplying weight to force the metal into the extents of the cavity. The sandcasting process is repeated with the altered cup and produces the castings seen in Figure 5.44.

Figure 5.44. Second Casting Attempt with Altered Pouring Cup

Further Observations

The increased cup and downsprue size, significantly improved the casting result, with the furthest extents of the cavity being reached. None of the ‘N’ features were successfully cast owing to their smaller profile compared to the rest of the pattern. Part of the ‘U’ on one of the spokes also failed to fully cast.

It is also thought that the molten metal is cooling too rapidly for air bubbles to escape through the risers in its molten state. To correct this, more risers will had to be added to the cavity for another casting attempt.

There are sunken deformations around the riser locations, as shown in Figure 5.45, as well as no evidence of material travelling up the risers. This defect is known as a shrinkage cavity, it is a depression on the surface or an internal void in the casting. It is caused by solidification shrinkage that limits the amount of molten metal available in the last region to solidify. Common areas for this problem are at the top of the casting cavity, as is the case with the Uno pulley wheel casting [25].

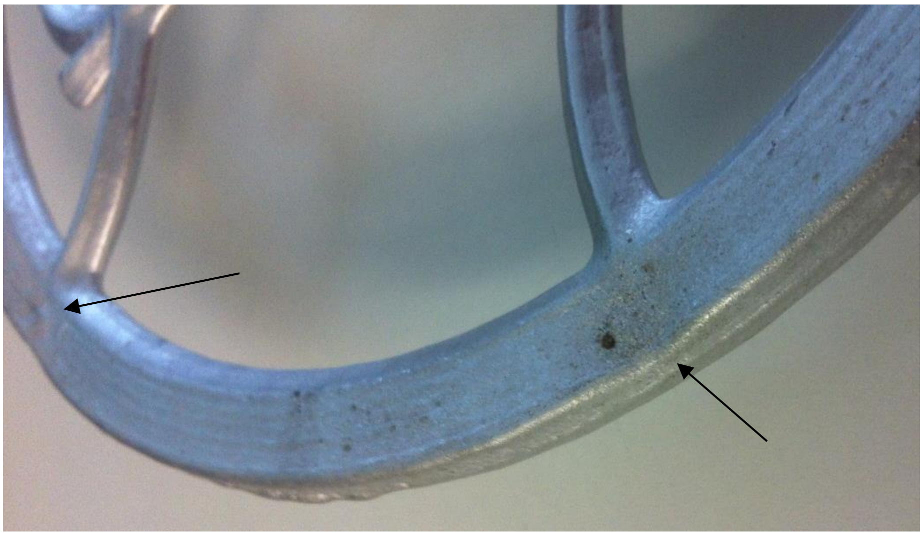


Figure 5.45. Deformations around Riser Locations

This would indicate that either the risers are not large enough, or the metal is not fluid enough to travel up them once it has reached the outer extremities of the cavity. By forming the risers by hand once the mould is made, they can be made larger and the complexity of compacting the sand in the cope is reduced as the rods are removed from the pattern geometry.

As discussed in the first casting attempt, the same cavity destruction that was displayed in Figure 5.41 reoccurred in the second casting. The pattern exhibits striations from being manufactured using FDM, which is the effect caused by building layer upon layer. It gives the core a rough feel which is likely pulling the sand with it upon ejection of the cavity. To rectify this issue, a coating of XTC-3D was applied to selected areas of the pattern. The product mentioned is pictured in Figure 5.46 below.

Figure 5.46. Smooth-On XTC-3D Coating (© Smooth-On)

XTC-3D is an epoxy resin which is for use on plastic AM parts. It is used for post processing and finishing of parts, and smoothes over the striations present on FDM parts. It was applied in thin coats to the pattern, with particular concentration upon the core and outer rim. The outer rim has clear striations which can be seen in Figure 5.47. Covering the surface with the epoxy will fill the sunken regions and give a flat surface to cast with.

Figure 5.47. Outer Rim Striations on Cast Part

Results of Changes Implemented

Increasing the temperature of the molten aluminium from 700°c to 750°c will keep it in a liquid state for longer, giving the casting an increased chance of success.

By introducing additional risers, it also allows gases to escape more easily than in previous castings. The additional risers are located at the top of the ‘O’ of each spoke, their hand made production shown in Figure 5.48. The original positions for the risers were also made by hand, and their size doubled from previous attempts where metal rods were used.

Figure 5.48. Hand Made Risers Production

The introduction of the XTC-3D epoxy resin made the removal of the pattern easier and allowed the core of the pattern to remain intact, giving the neatest cavity pattern produced thus far. Figure 5.49 shows the finished cavity, ready for pouring the molten metal into.

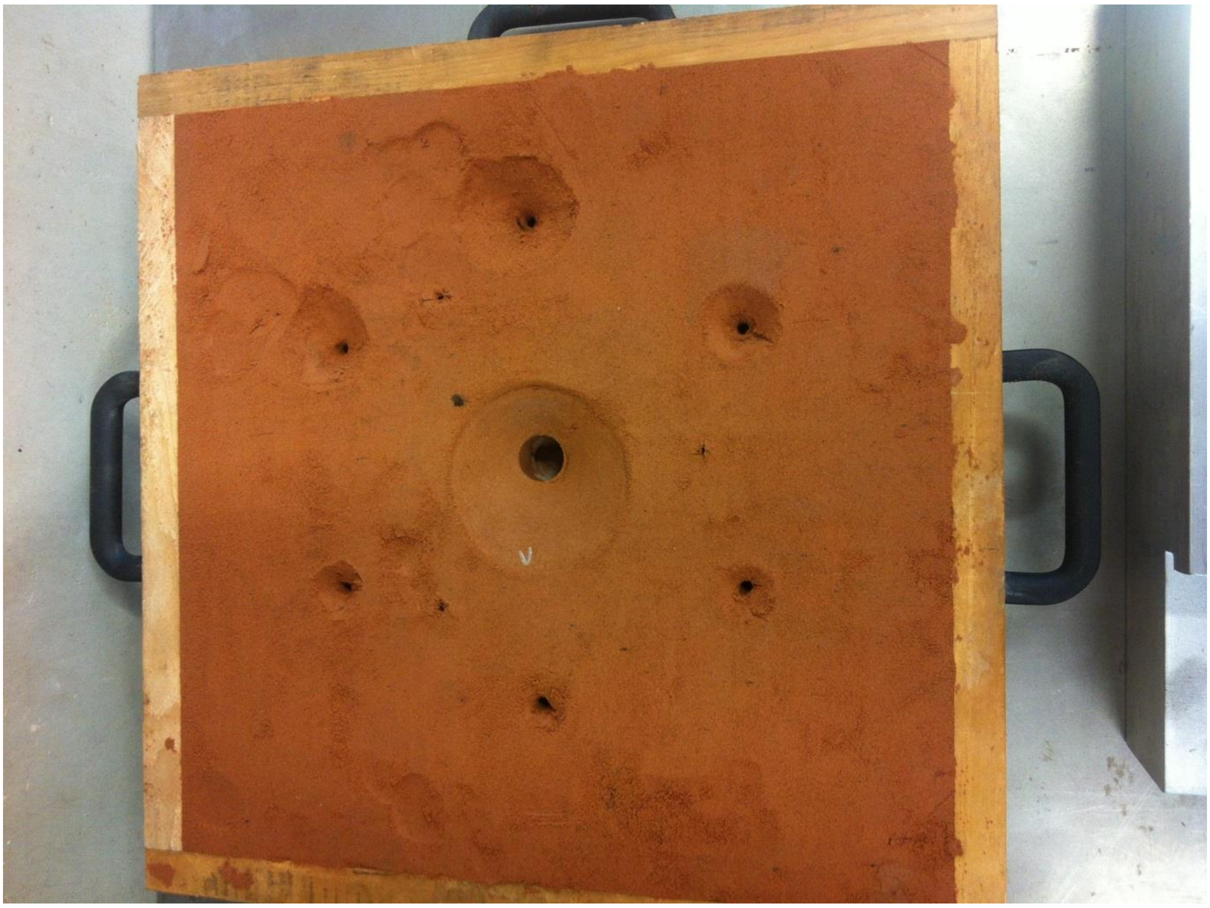


Figure 5.49. Plan View of Sand Casting Mould Ready for Pouring with Large Pouring Cup and Hand Made Risers

The culmination of changes resulted in the casting shown in Figure 5.50. The part has been separated from its pouring cup and risers by use of a hacksaw and file. It has also had its core shaft bore drilled out. It required further post processing though as it was an unsuccessful casting due to the failure of the ‘N’ sections. Further post processing can be carried out on a more complete casting.

Figure 5.50. Sandcast Result after use of Additional Risers, Increased Pouring Temperature and XTC-3D Coating

From Figure 5.50 it can be seen that the striations have been removed successfully, though the surface finish is not completely flat as the application of the epoxy was done by hand and thus is not perfect. It can be flattened by use of a file or other abrasive techniques.

Given that there was a complete spoke casting in this instance, it would indicate that the issue of the failed sections lies within the material ability to flow, rather than the design constraints of the cross sectional area of the ‘N’ segment of the pattern.

Material Reconsiderations

The material that was being used to make the castings is sourced from offcuts of extruded bars used in the manufacture of machined parts not originally intended for casting. This material was used as it was the most available resource and was intended to prove that casting of a part like the Uno pulley wheel was possible. The material suitability with regards to physical properties was not a leading factor in its design as it is subjected to low loads when in operational use.

It was considered that by using a more suitable material, i.e. one which had originally been intended for a casting process, there would be an increase in the success of the casting of the part. Thus a car aluminium alloy wheel was obtained, cleaned and broken down to be used for the next casting attempt. Alloy wheels are made from 2000 series aluminium [47] and are usually die cast. Ideally 356 aluminium alloy would be used for sand casting [48] specifically, though none was available from local scrapyards. Also the purpose of this exercise was not to use the ideal materials, but to use suitable materials which meet all of the functional requirements and can be successfully cast within the given parameters of the pattern.

Casting Using an Aluminium Alloy Designed for Casting

As before the 2000 series aluminium was heated to 750°c in the furnace. Though as there was issues with the ‘N’ section it was decided to trial different riser positions on each spoke to find out which combination worked best, if at all. The positions on each spoke are marked in Figure 5.51. The use of the 2000 series alloy resulted in a much better cast, with the molten metal in the pouring cup visibly staying in a liquid state for much longer. This gives rise to fully cast ‘N’ sections in the internals of all three spokes for the first time. Unfortunately the placement of one of the risers caused part of the mould to collapse and resulted in a missing branch of the ‘U’.

Figure 5.51. Marked Locations of Test Risers

Given the better flow gained by using the different alloy, the molten metal moved more freely and travelled up the smaller risers to a small extent, as shown in Figure 5.52. These ‘tabs’ will require post processing to remove them. It is clear from examining the locations of the tabs that the additional risers present on the spokes, that one on the top of the ‘O’ is necessary and a further one on the ‘N’ yields the desired full casting.

Figure 5.52. Risers to be Filed Down

Final Casting Attempt

The final casting attempt varies from the first attempt in a number of ways:

1. The material used is more appropriate for casting.
2. The temperature of the furnace is higher, 750°c rather than 700°c. This makes the metal stay in its molten state for longer to allow it to reach the outer limits of the cavity.
3. The pattern is coated in an epoxy resin to smooth out areas with striations from being fabricated in layers. This allows for easier ejection from the mould and reduces the chance of the cavity crumbling upon the pattern being

removed. Less damaged areas in the cavity results in less post processing on the casting.

4. In the case of the Uno pulley wheel, having an in-build gating system proved to be more of a hindrance when compacting the sand and for removal from the mould, thus it was removed.
5. The risers were made by hand after they were removed from the pattern, and additional smaller risers were placed in the best places on the internals of the spokes.
6. A larger pouring cup was used to give quicker pouring, reducing time for the metal to reach the outer limits of the mould. It also increased the weight force of the material pushing the metal to the extremities.

By implementing these changes in pattern design and sandcasting practice, it resulted in the casting picture in Figure 5.53. This resulted in a casting with all features being fully formed as desired.

Figure 5.53. Final Sand Casting Result of Uno Pulley Wheel

Full Post processing Requirements

Typical post processing actions for sand castings are carried out on automatic machinery to clean the part up to its finished operating state. Though in the case of the pulley, this had to be done manually. As with all casting manufacturing techniques, there is a need for post processing to finish the part, the following lists some simple steps to clean up the part (Figure 5.54):

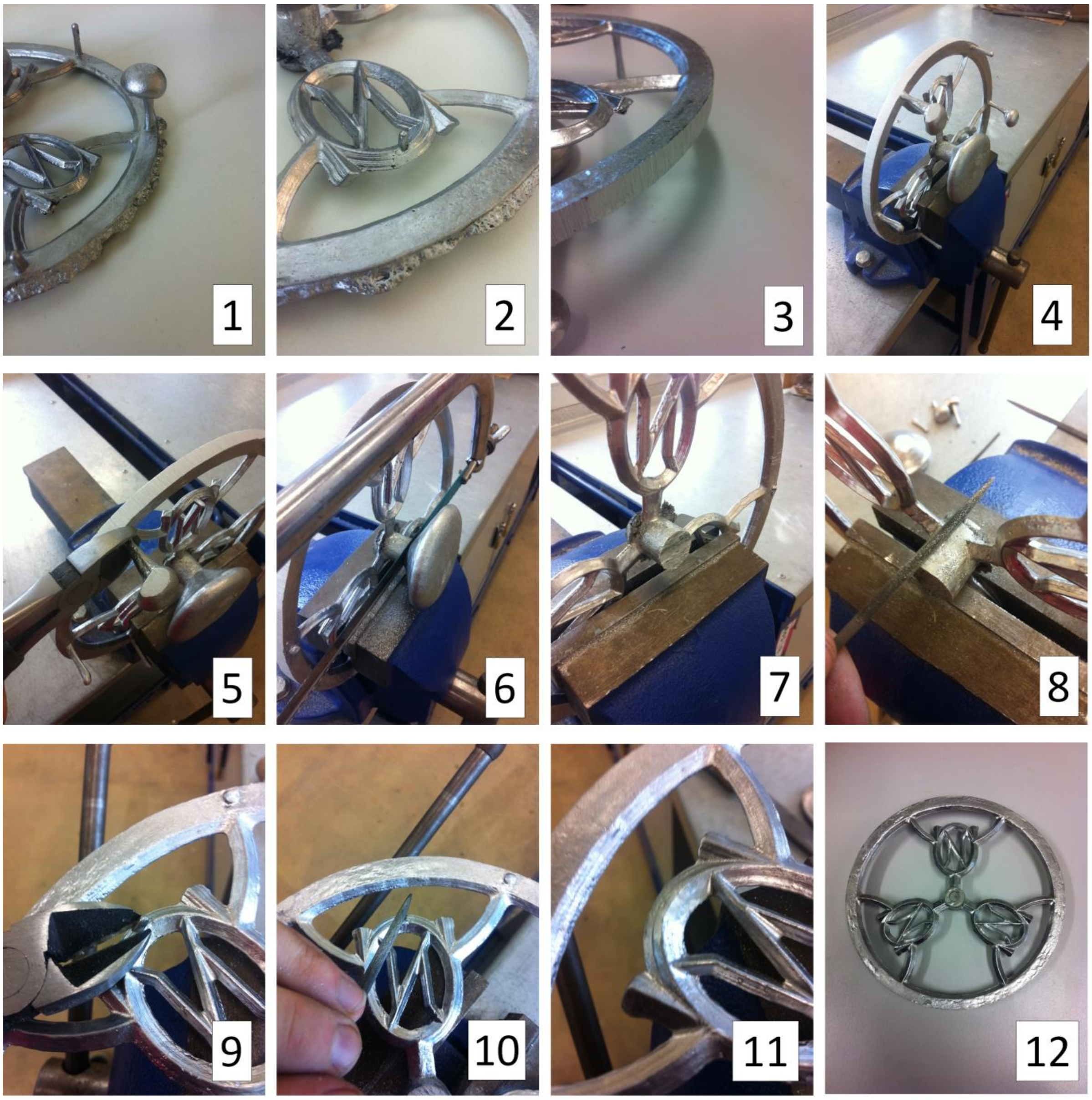


Figure 5.54. Sand Casting Post Processing of Uno Pulley Wheel

(1-2). Features on the casting which are not part of the final part must be identified. Such as risers and other gateway features, as well as any parts which are a result of a damaged mould.

(3). The extra material present form the damaged mould on the outer rim is removed by a belt sander to produce a flat circular surface.

(4-5). The large risers on the outer rim are removed by snips and then filed down flat to the same level as the rest of the rim surface.

(6-7). The pouring cup is removed by using a hacksaw, then a file removes any burrs from the cut surface.

(8). The extra material on the internal spoke of the wheel had to be removed with a small file.

(9-11) The risers on the internal spoke geometry had to be filed down carefully with a small file, care was taken around the fine features.

(12) With all other post processing need met, the final step was to drill a centre bore for the wheel to be mounted on a shaft. (Figure 5.55)

ease.

Figure 5.55. Post Processed Casting of Uno Pulley Wheel

Given that the pulley wheel is a scaled down version of the part, it was deemed that it was too small in terms of thickness of the rim to be able to machine a profile for the v-belt, though as this is just an exercise to prove that AM technologies are capable of producing a functional part, it was not a problem. A full scale version of the part could be cast given access to an FDM machine with a large enough build area, or the pattern could be made up of smaller sections and glued together to make a full sided casting. Unto which a profile for the v-belt could be machined with greater ease.

5.6. Further Project Work

There are numerous options to realise a metal component by use of an AM technique. It is not restricted to printing a pattern for use in sand casting as was demonstrated in this case study. As mentioned previously, the use of FDM to create the pattern for sandcasting was an option selected due to the constraints of available in-house resources and may not have been the best course of action in manufacturing the pulley wheel. An exploration into other manufacturing techniques that incorporate AM in their process and improve upon the original traditional method of production would be of benefit. A study of which options are cheapest, hold the quickest lead times, or produce the highest quality, dimensionally accurate parts could be carried out to find out which would be the best option for production of the pulley wheel. However, this would be limited to parts that are geometrically similar to the Uno pulley wheel. There is of course scope for processes to be better suited to what the part requirements are for the component to be manufactured.

The application of AM in a casting process to produce metal parts is regarded as rapid casting (RC), and is what is known as an indirect method of manufacturing parts. It is done typically through the combination of AM and traditional manufacturing techniques [49].

5.6.1. AM Pattern

Expendable mould castings require a pattern to form the mould material around it. The key part in casting is to design and produce a pattern used to create moulds in which to cast metal. The design and preparation of core boxes and gating systems which determine cast quality are highly time consuming, especially in the case of complex parts [49]. Through the use of AM, it is possible to manufacture the required pattern, reducing the total time for part production, as well as eliminating the use of tooling, saving on costs.

Sand Casting

AM is primarily used in sand casting to produce the pattern which is used to form the mould cavity. In the instance of the pulley wheel, as discussed in Chapter 6.4, it was deemed that an FDM part was best suited given the availability of resources. Patterns can be made using a number of AM processes such as FDM, SL or SLS.

Each process incurs different costs and timescales which could be factors in deciding which to use, alongside print quality and if the part produced will meet the requirements of sand casting. FDM for example, produces a surface finish with a surface texture as the plastic is deposited in a layer-by-layer manner. It is not a critical issue for use with sandcasting, though if a part of fine detail is to be produced then alternative AM methods would need to be employed to gain a better quality surface finish [50].

Investment Casting

Wax patterns can be fabricated using AM techniques instead of the traditional method of injection moulding the wax. This removes the need for a mould to create the pattern, which reduces the overall lead time it takes to create a part. Traditional investment casting produces high quality, dimensionally accurate metal parts, though its economic advantages are limited to mass production [49]. By employing AM manufactured patterns, it realises the advantages of using investment casting, but can maintain them for use in small and medium batch sizes.

Another method of making sacrificial wax patterns is to use an AM technology to fabricate a pattern then cast a Room Temperature Vulcanisation (RTV) silicone rubber mould. From the rubber mould, wax patterns are cast for use in the investment casting process. This method is demonstrated in Figure 5.56 [51].

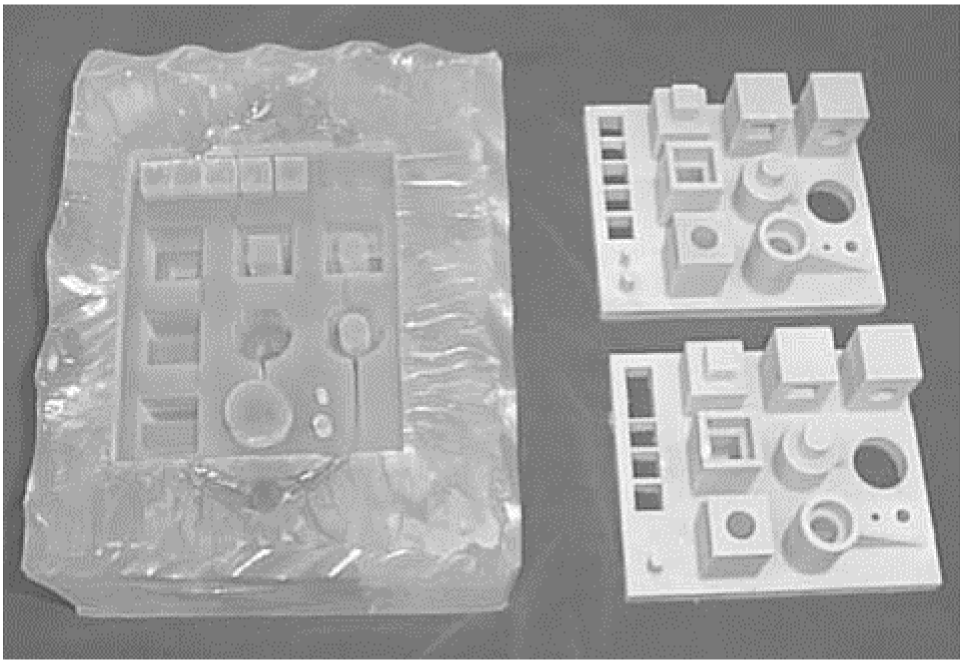


Figure 5.56. Silicone Rubber Mould and Wax Patterns

AM Investment Casting use on Uno Pulley wheel

As highlighted previously in Chapter 6.4 when discussing the disadvantages of the use of an FDM pattern for sandcasting, the incorporated use of the gating system turned out to be more of a hindrance than a help. It is acknowledged that this may be down to part suitability and that the particular geometry of the pulley wheel, being a spindly design, was too fragile to withstand the compaction of the sand mould.

Investment casting is more suited for the production of fine and complex parts as it does not have the constraints that sandcasting does in the form of parting line placement for mould separation. Were the pulley wheel to have been fabricated in wax with the gating system incorporated, then it is believed that a more successful, higher quality finish could have been achieved, had the resources been available to do so.

5.6.2. AM Ceramic Moulds/ Sand Sintering

There are many advantages that AM technologies offer, and the opportunities created by these processes give rise to a new way of approaching traditional manufacturing techniques. AM makes it possible to break the constraints that exist in conventional tooling processes [10].Conventional fabrication limits design freedom because the product must adhere to the constraints placed upon it by the restrictions of subtractive manufacturing processes such as computerised numerical control (CNC) milling. However, by implementing AM, complex geometries can be adopted at the design phase, since moulding constraints are no longer an issue. For example traditional moulding requires the consideration of draft angles, parting line locations, wall thickness, filleted corners, whereas AM does not [52].

Applications for Sand Casting

The manufacture of ceramic moulds by using SLS with a ceramic powder is a possible route for producing metal parts. It is applicable for casting nonferrous metals such as aluminium, zinc and magnesium alloys. These moulds are disposable as it requires breaking them to remove a cast part [53]. By manufacturing these moulds using AM technologies, the build time can be reduced by up to 90%. The materials used to make these moulds range from alumina ceramics to zirconia ceramics and can withstand temperatures between 1538°C and 1760°C [54]. The complete mould can be sintered in two or more parts, with any cores either being sintered separately or built into the outer shell. This allows for high complexity moulds to be produced and reduces design effort in designing a core that would fit into the mould [55]. Figure 5.57 [56] below is an example of a mould which has been manufactured with an in-built core.

Figure 5.57. Examples of Moulds for Direct Casting of Aluminium Produced by Additive Manufacture

Advantages

The biggest advantage of being able to AM moulds in a ceramic material is that it cuts out the lengthy process of forming the mould from a pattern or indirectly producing the ceramic mould by using other methods, AM or otherwise. To be able to print a mould ready for casting in the desired material straight away drastically reduces lead times to 7-10 business days [57] for part production and saves on costs of multiple operators in a traditional process. There is only need for one staff member to print the mould and pour the material, as opposed to the multiple personnel required to manufacture using the conventional methods. It reduces the amount of steps required in the manufacturing process as can be seen by a comparison of the traditional methods, shown in Figure 5.58 [58], against the use of the rapid casting technique seen in Figure 5.59 [59].

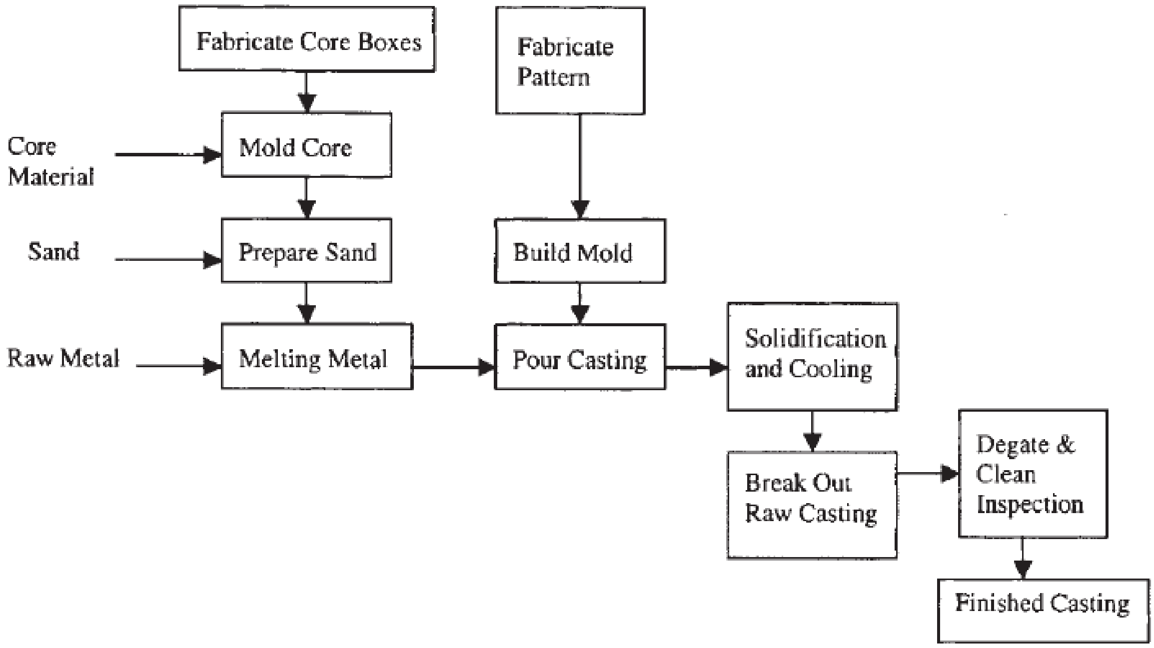


Figure 5.58. Production Sequence in Sand Casting

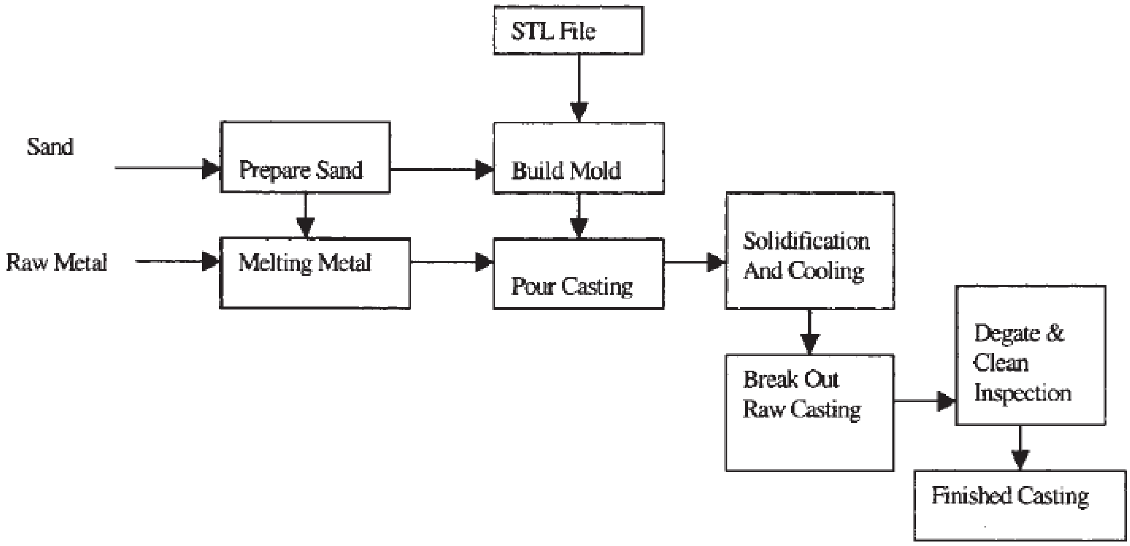


Figure 5.59. Production Sequence in Rapid Casting Process

Limitations

As with any current AM technology, there are limitations and faults. An issue with laser sintered shells is the difficulty with, or in being able to examine the internal surfaces before casting without the use of CT or endoscopy [60]. This would also give rise to difficulties in clean unsintered ceramic power out of complex inner geometries. Depending on the complexity of the mould, it may be required that it be made up of multiple parts to allow the powder removal [55].

Applications for Investment Casting

With regards to investment casting, this process cuts out the lengthy steps of pattern making, either by injection moulding or 3D wax printing, as well as avoiding the iterative process of slurrying, sanding and drying of the pattern, as demonstrated in Figure 5.60 [60].

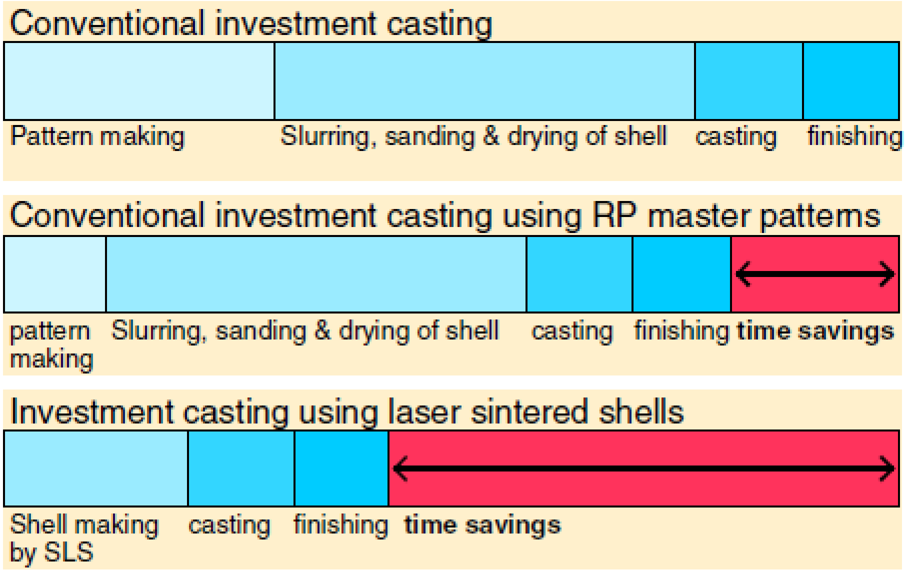


Figure 5.60. Comparison of Investment Casting Process

The surface finish which is produced using an AM ceramic mould is significantly rougher than that of a part produced using the traditional investment casting method which may need additional post processing to correct this, as described in the casting of a whirl chamber of a diesel engine, seen in Figure 5.61 [60]. The surface roughness of a part cast using the ceramic laser sintered mould is of a poorer quality (R_a ~ 12 μm) compared to traditional investment casting methods (R_a ~ 6.3 μm) [60].

Figure 5.61. Whirl Chamber of a Diesel Engine Cast in X15CrNiSi25 20

Suitability for use on Uno Pulley Wheel Casting

Had this method of manufacturing the mould been available for the casting of the pulley wheel then it would be advantageous to incorporate all gating systems into the mould, in a similar fashion as was attempted with the FDM pattern for sand moulding, though in a negative sense as the mould is the inverse of the pattern. As the process has no requirements for sand compaction or human intervention other than to clean out the loose ceramic powder from the finished sintered mould, it would mean that there is little chance of the gating system being damaged. The only likelihood of failure would be if it was designed inappropriately, and susceptible to breaking. As a whole, it is a better suited process to be able to introduce all the aspects of the gating system to a 3D printed mould, with a higher chance of success than what was carried out on the Uno pulley sandcast.

5.6.3. Direct Manufacturing

The manufacture of metal parts using AM is not limited to the combined use of an additive technology in a traditional manufacturing method. Direct Metal Laser Sintering (DMLS) was the first commercial rapid prototyping method to produce metal parts in a single process. It uses metal powder (nominally 20µm diameter particle size), without the use of binder of fluxing agent, which is melted by a focused high power laser beam giving it the properties of the original material. This eliminates need of binders and skips burn-off and infiltration steps necessary with other additive metal processes. This method produces a 95% dense steel part, compared to that of SLS, at 70% [61].

The part is fabricated layer-by-layer. The machine consists of a supply section, and a sintering, or build area (Figure 5.62 [62]). At each layer sintering step, the powder dispenser system moves upward to provide the required raw material for the recoater arm to spread onto the build platform. The laser then traces the cross sectional area of the part slice to melt and fuse that layer of the component. The piston of the build platform then moves down a layer thickness and the process is repeated, layer by layer until the whole part is complete. The biggest issue with the DMLS process is the build time. Parts of even small-moderate size may require more than 6–12 hours of processing [63].

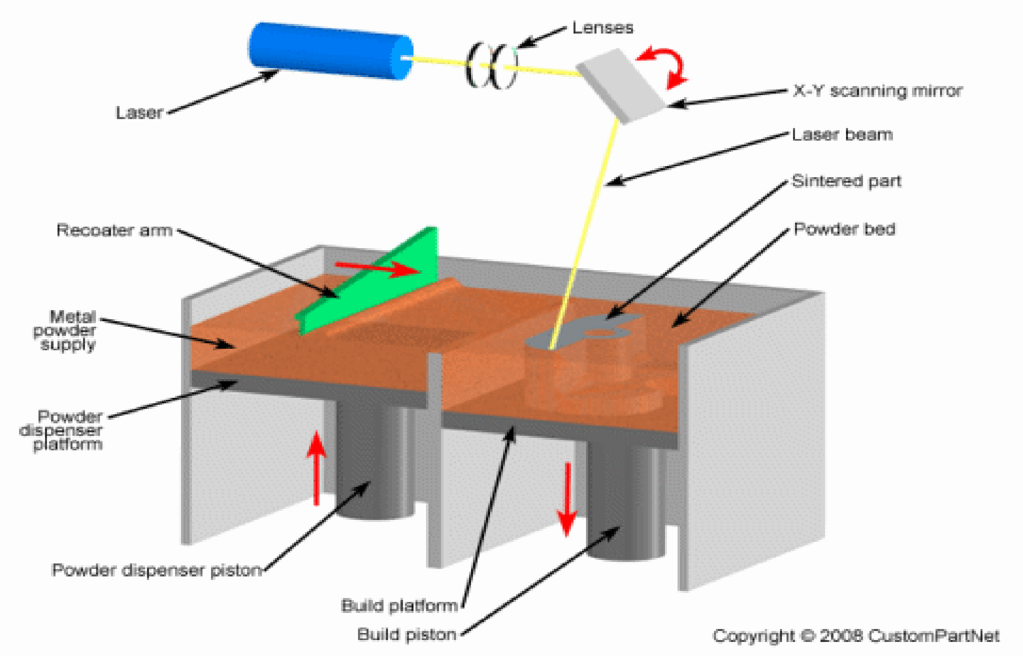


Figure 5.62. Direct Metal Laser Sintering

A benefit of the DMLS process is high detail resolution due to the use of finer powder, thus smaller layers thicknesses are possible. This capability allows for more intricate part shapes. The materials that are available include alloy steels, stainless steel, tool steel, aluminium, titanium, bronze and cobalt chrome [61].

The use of DMLS to create functional metal parts typically costs much more than other metal prototyping techniques and is not suitable for manufacturing large parts. Parts made by DMLS can be easily machined, polished and etched etc. It is best suited for small batch manufacturing of machinable parts or functional prototypes [64]. The process is capable of an accuracy of ±50µm and though it can be machined or polished if necessary, it produces surfaces which require little to no post processing [55].

There are DMLS machines with build volumes large enough to manufacture the full sized Uno pulley wheel (305mm diameter), such as the EOSINT M 400 which offers a 400 x 400 x 400mm build volume. It is able to directly manufacture the part in a range of materials including Aluminium (AlSi10Mg, a typical casting alloy) as well as stainless steel [65].

Shapeways Metal Part Fabrication Process

The bureau service Shapeways can be used to directly upload an *stl file of the desired component to be manufactured in stainless steel using a process called binder jet printing. This process uses stainless steel powder which is deposited in a thin layer over a print bed, onto which a liquid resin, or binder is applied to the cross section of the layer. The next layer of powder is deposited then the process repeats until the part is complete. It is in what's known as a green state as it is fragile, like brittle clay, or wet sand. This has to be considered when designing models which are made via this process as additional support may need to be designed in. The model can be removed from the loose powder once it has been put in an oven and cured, which removes the binder by melting it. The model is then transferred into sand for support and infused with bronze at 1400°C, completing the manufacturing process [66].

This option was available for manufacture of the Uno pulley wheel, though compared to the method used it was not as cost effective. It also has restrictions when uploading a design, such as the thickness of features it can build. Shapeways will give a visual model of features which are suspect of failing during the fabrication process (Figure 5.63 [67]). In this instance the outer rim of the v-belt profile is suspect. This can be easily avoided by uploading a model without the profile, then machine it in afterwards.

Figure 5.63. Areas on Uploaded Shapeways Model of Uno Pulley Wheel which are Suspect of Failing during Printing Process

Cost Breakdown Comparison

The cost of the Uno pulley wheel manufactured in stainless steel from Shapeways is **£943.04** (July 2015). The estimated costs of Sandcasting below:

FDM Pattern (2 Halves) = **£146.55** (quote provided by Lancaster University)

Aluminium rate = £1,090 per 1000kg (June 2015 [68])

Aluminium Required = 1kg

Aluminium cost = **£1.09**

Safety Equipment (approximation) = **£60**

Note: Safety equipment considers items like face shield, leather apron, gloves, boots etc

O.B.B. oil bonded moulding sand = **£24.50** for 25kg (July 2015 [69])

Total Sandcasting Cost = **£232.12**

The total cost for sandcasting is significantly cheaper than direct manufacturing of the part using Shapeways (estimated £710.90 cheaper). Though it does require more effort, it can be done multiple times once the materials have been purchased. Labour cost have been discounted as it is seen as a DIY exercise for ones’ own benefit.

6. Investigation of Scanned Geometry Collection Methods

Difficulties arose when attempting to scan a 3D model of the Uno pulley wheel. As was explained in Chapter 5.4, both the structured light and the IRSL methods of scanning failed to obtain a full 360° of the wheel.

These scanners are a cheap option, explored to investigate if they are of a high enough quality to provide accessibility to an inexperienced user to the reverse engineering and manufacturing process. For example, desktop printers are becoming more and more accessible to both engineers and non-engineers to be able to gain access into the 3D printing world. They are becoming cheaper and the quality of print available form them is improving all the time. The Ultimaker2 used to print the pattern used for sandcasting the Uno pulley wheel was £1,457.70 excluding VAT, and is capable of a layer thickness of 20µm [70] It can produce high quality prints that previously were not available for machines in the lower end of the price range.

This opens up the possibilities in the way that a person with no access to multi thousand pound machines can endeavour to reverse engineer components to manufacture usable parts. However there is a need to explore how well lower cost 3D scanning technologies can digitise the real world parts in this reverse engineering process. As seen in Chapter 5.4 there was an attempt by the author to implement both structured light scanning as well as handheld IR scanning to digitise the pulley wheel. Both of which were unsuccessful to some extents and another method of capturing the geometry to a 3D model was used.

6.1. Test Cube

A test piece was designed to explore the capabilities of low cost scanning equipment which was available to the author (Figure 6.1). Sections of the test piece were designed to determine how well each method of scanning could cope with the following parameters:

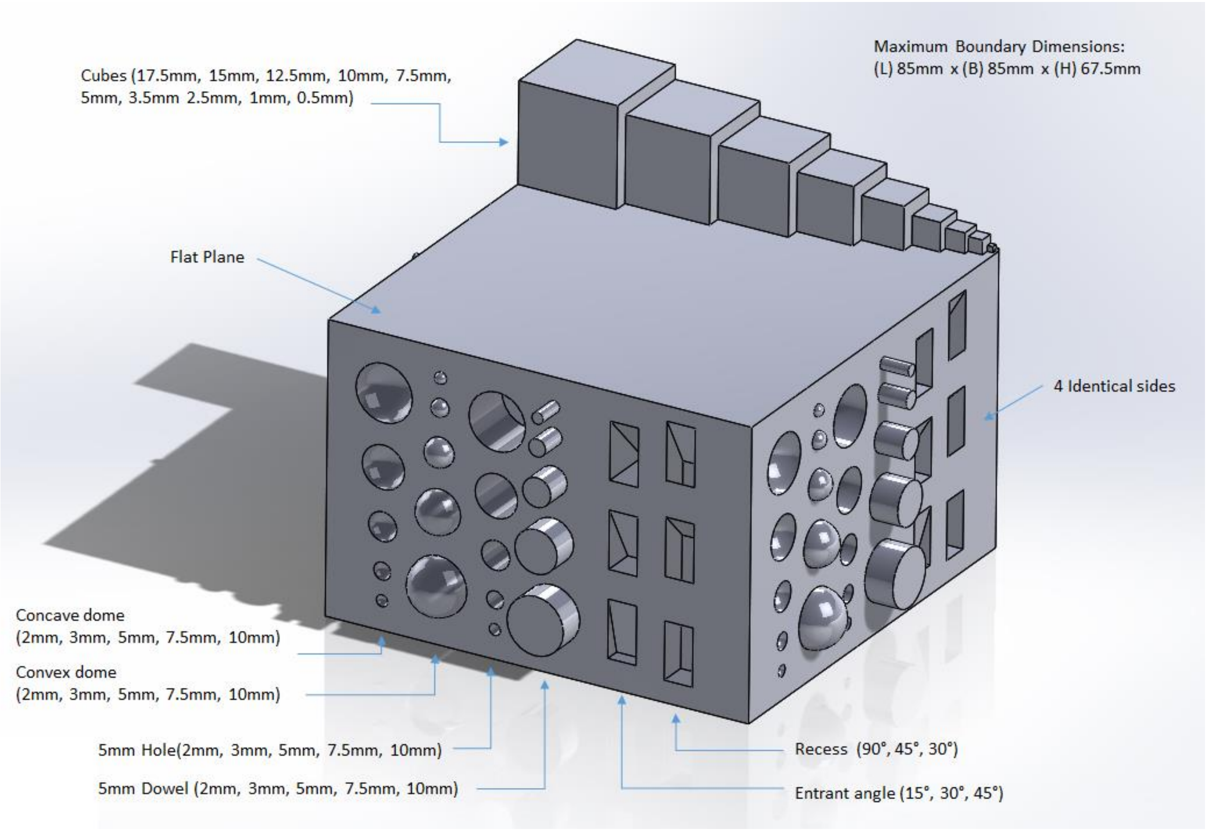


Figure 6.1. Test Cube SolidWorks Model Feature Annotation

- Planar surfaces
- Holes
- Extruded profiles
- Undercuts
- Colour

- Reflectivity

To test as many variables as possible in one go, as well as considering what effect different colours and levels of reflectivity would have on the scanners, a cube shape was used to produce features identically on four sides. The model was produced using SLS, giving it a matte white finish. Two sides were painted black to test the effect of colour, and one of each colour was coated in a clear epoxy which made them reflective to test reflectivity (Figure 6.2).

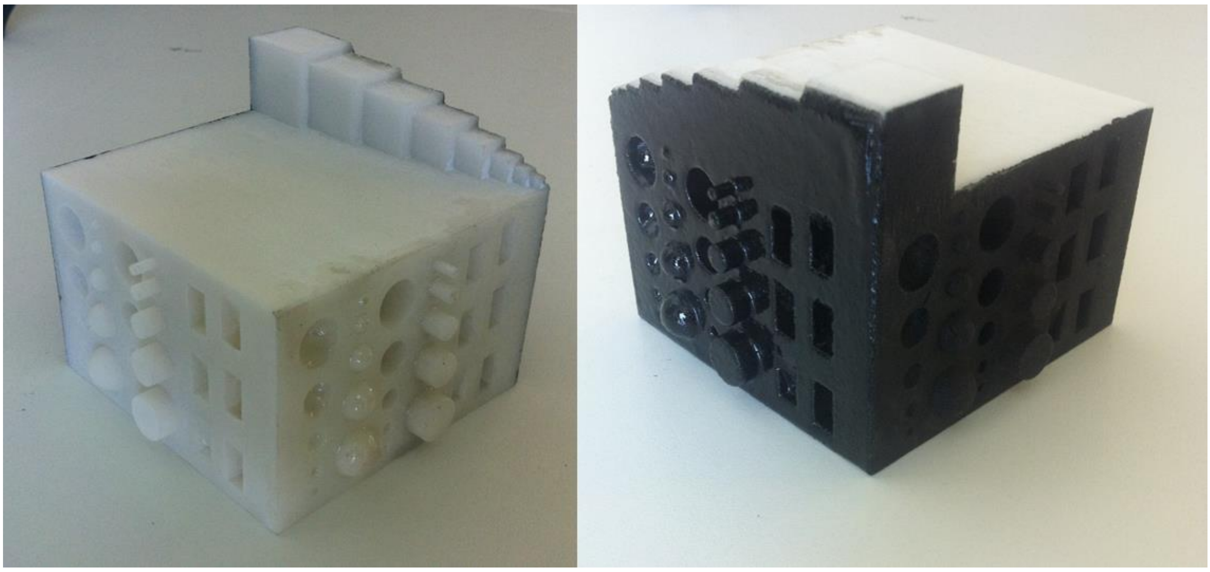


Figure 6.2. Painted & Coated SLS Test Cube

A large planar surface was incorporated because scanners make data in point clouds which translate to polygonal meshes. These meshes do not accurately create on flat surface. Instead they will be made of lots of triangles which all vary slightly in their adjacent angles, thus giving a slight uneven surface effect.

A series of cubes ascending in size from 0.5mm (the smallest size the available SLS machine is capable of creating features [71]) to 17.5mm was placed on the planar surface to assess the dimensional accuracy capabilities of each scanner. Both concave and convex domes were added to measure freeform surface capture, especially on the reflective panels. Holes and dowels in varying sizes were used to assess ability to capture holes and features as well as to what dimensional extent each scanner was capable of.

Undercuts were tested in the form of recesses which had varying entrant angle steepness (Figure 6.3 and Figure 6.4).

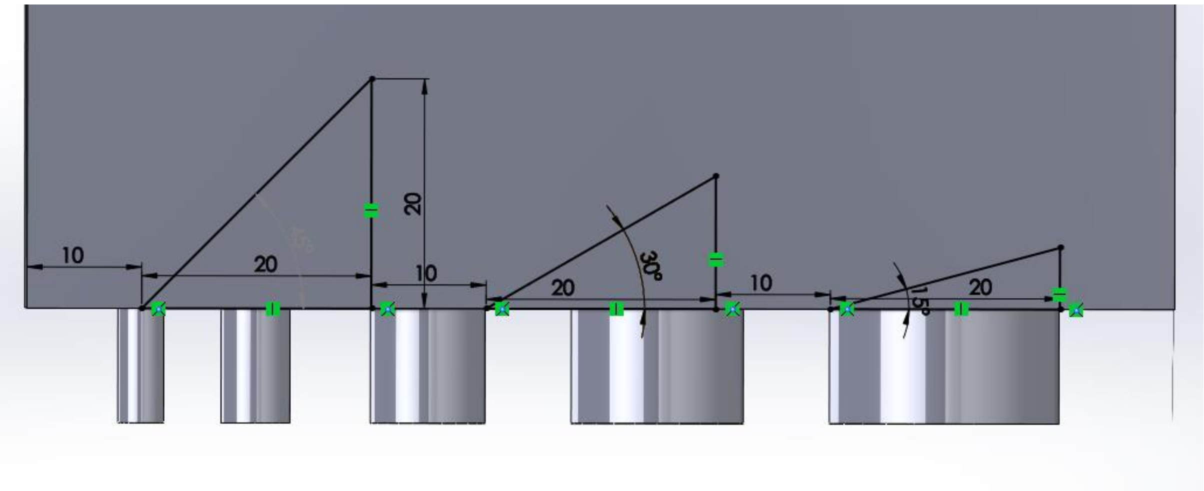


Figure 6.3. Undercut Entrant Angles

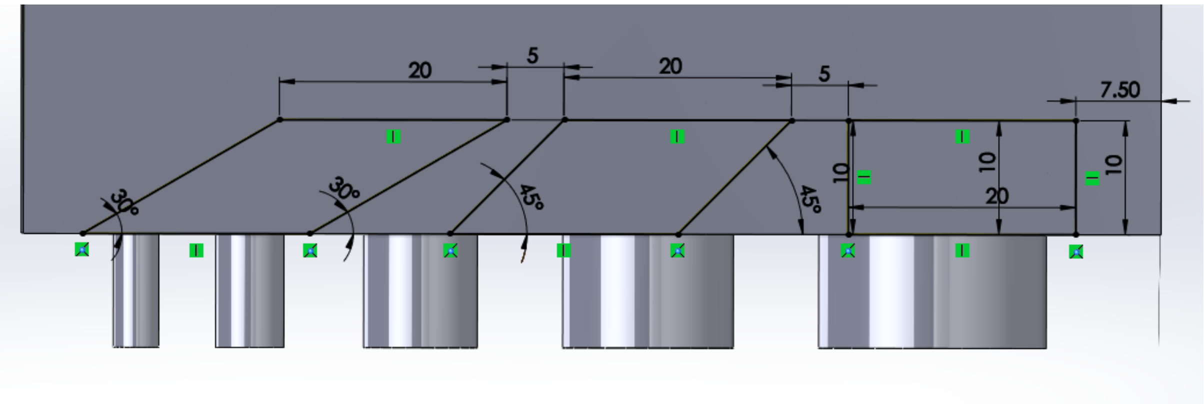
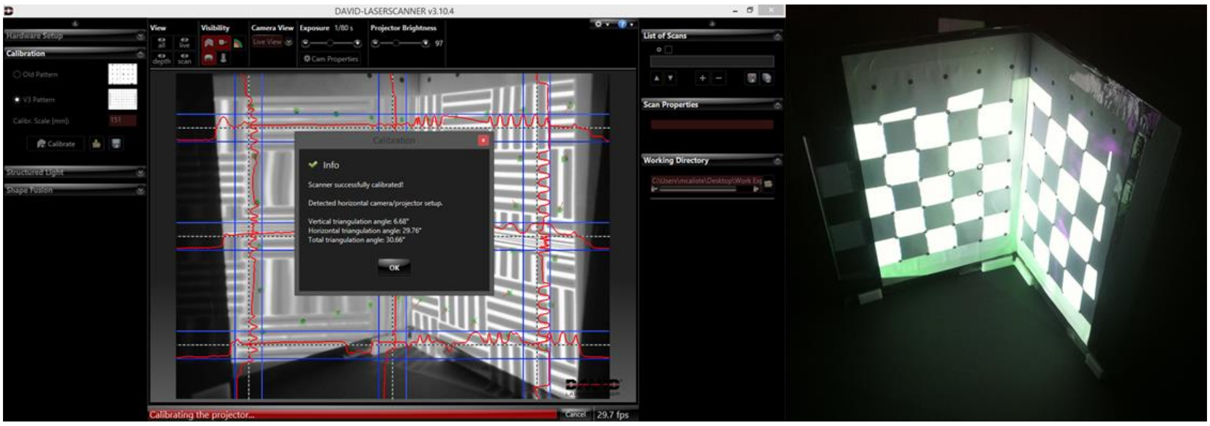


Figure 6.4. Angled Recess Feature

6.1. Structured Light Scanning

To scan in the test cube geometry the David Laserscanner was set up in the same manneras mentioned in Chapter 5.4.4., when scanning the Uno pulley wheel (Figure 6.5). The camera and projector had to be calibrated so that the software can calculate thier positions relative to one another (Figure 6.6).

Figure 6.5. Structured Light Setup



Info

Scanner successfully calibrated!

Detected horizontal camera/projector setup.

Vertical triangulation angle: 6.68°
Horizontal triangulation angle: 29.76°
Total triangulation angle: 30.66°

Calibrating the projector...

Figure 6.6. David Laserscanner Calibrated

To make the geometry collection easier, the test cube was placed on a rotating plate, which can be seen in (Figure 6.5). This keeps the part to be scanned rotating on a fixed axis, making the stitching together of individual scans slightly easier. The brightness of the projector as well as the camera exposure rate has to be balanced carefully to be able to capture as much of the part to be scanned as possible. Multiple scans of the part were carried out using different combinations of these factors until the right balance was found. The best combination is dependent on the lighting levels of the area being used for the scanning. It is easiest to use a completely dark room where the light levels do not vary to obtain consistent scanning over a period of time.

The resultant scan is limited to what the camera can see, it will only pick up surfaces which have the structured light from the projector shining onto it, thus if there is a shadow cast by any features, then the shadowed area will not be present in the scan data (Figure 6.7). This means that for especially complex geometries, multiple scans will have to be carried out to be able to pick up areas all around protruding features, as well as at specific angles to capture the internal geometry of hole features.

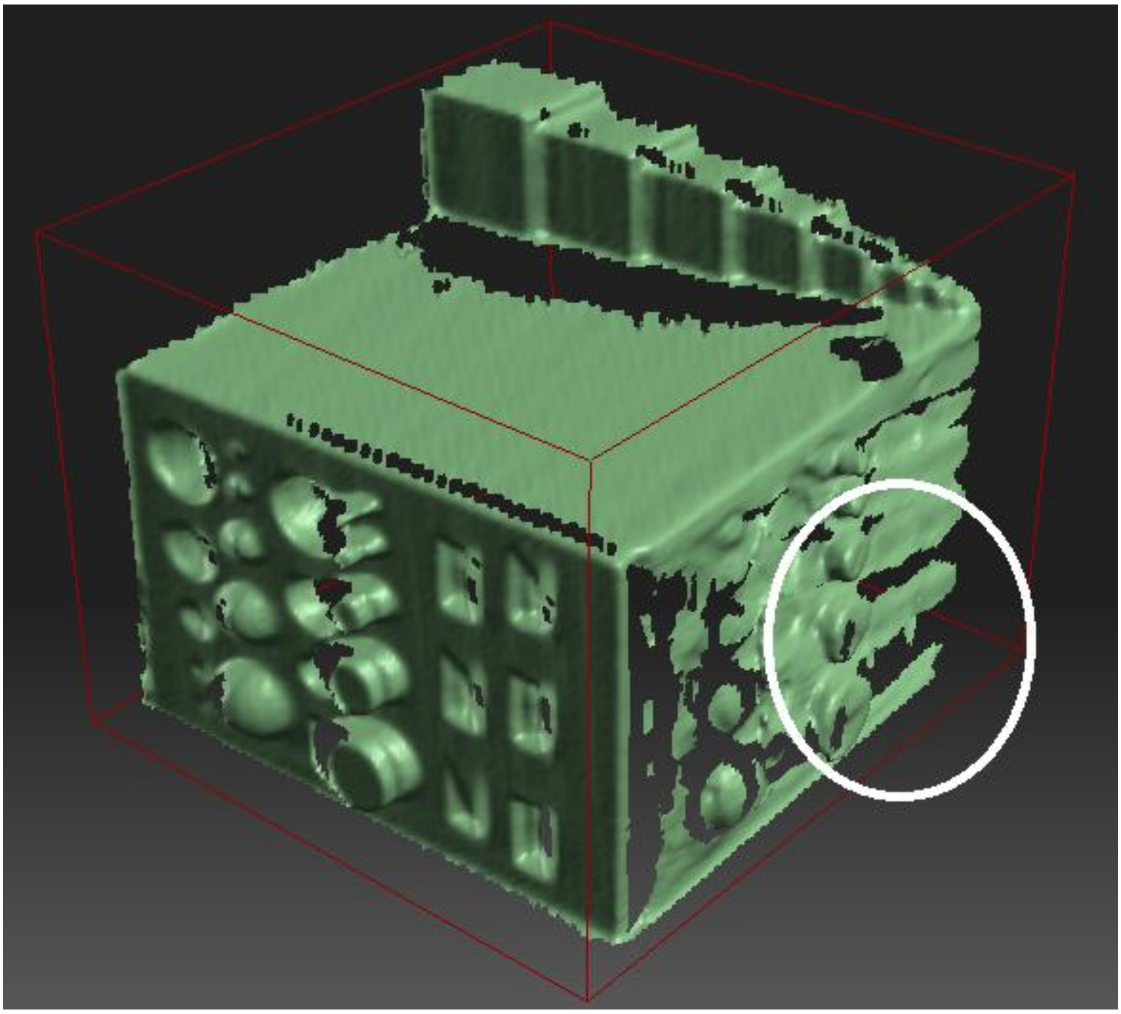


Figure 6.7. Feature Casting a Shadow on First Structured Light Scan of Test Cube

When stitching the multiple scans together using the David software it automatically joins the latest scan to the previous one, so it is best to go around the part being scanned in one direction in as small increments as is necessary for full geometry capture. If the increment is too large, it is common that there is not enough common points between the latest and previous scan to align them together properly (Figure 6.8). It is especially troublesome on a part like the test cube where it has identical features all around the outer faces. The only point of reference to show that the part was being rotated was the series of cubes on the top, so it was critical that they were part of each scan. There is an option when aligning individual scans to use 'contact pair alignment' which allows the selection of the same point of the model on each of the scans to use as a point to align them both around. This option means that fine tuning of the arrangements can be carried out. A 'global fine tuning' alignment option is available to fine tune the alignment of the scans once they are placed as desired.

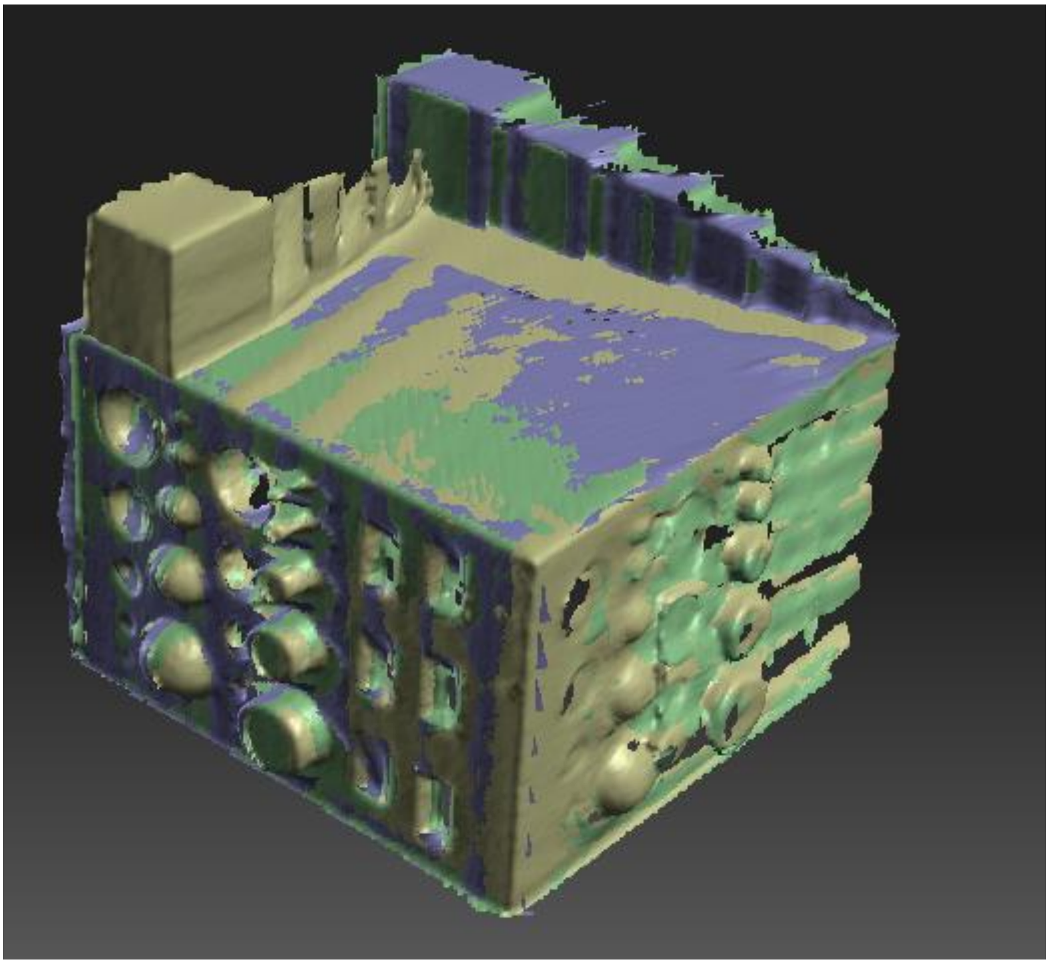


Figure 6.8. Misalignment of Test Cube Scans

It was noticed when carrying out the individual scans that there were some evident issues with the structured light method. Firstly the extruded features that had been scanned developed a draft, which is not present in the model being scanned (Figure 6.9). It is presumed that these draft angles are caused by the limitation of detail which can be captured using the structured light. It was also apparent when attempting to scan the black reflective face that the camera struggled to pick up the light patterns being projected (Figure 6.10). It is believed that the light absorption qualities of the black and the light scattering properties if the epoxy coating is more than the camera is capable of handling.

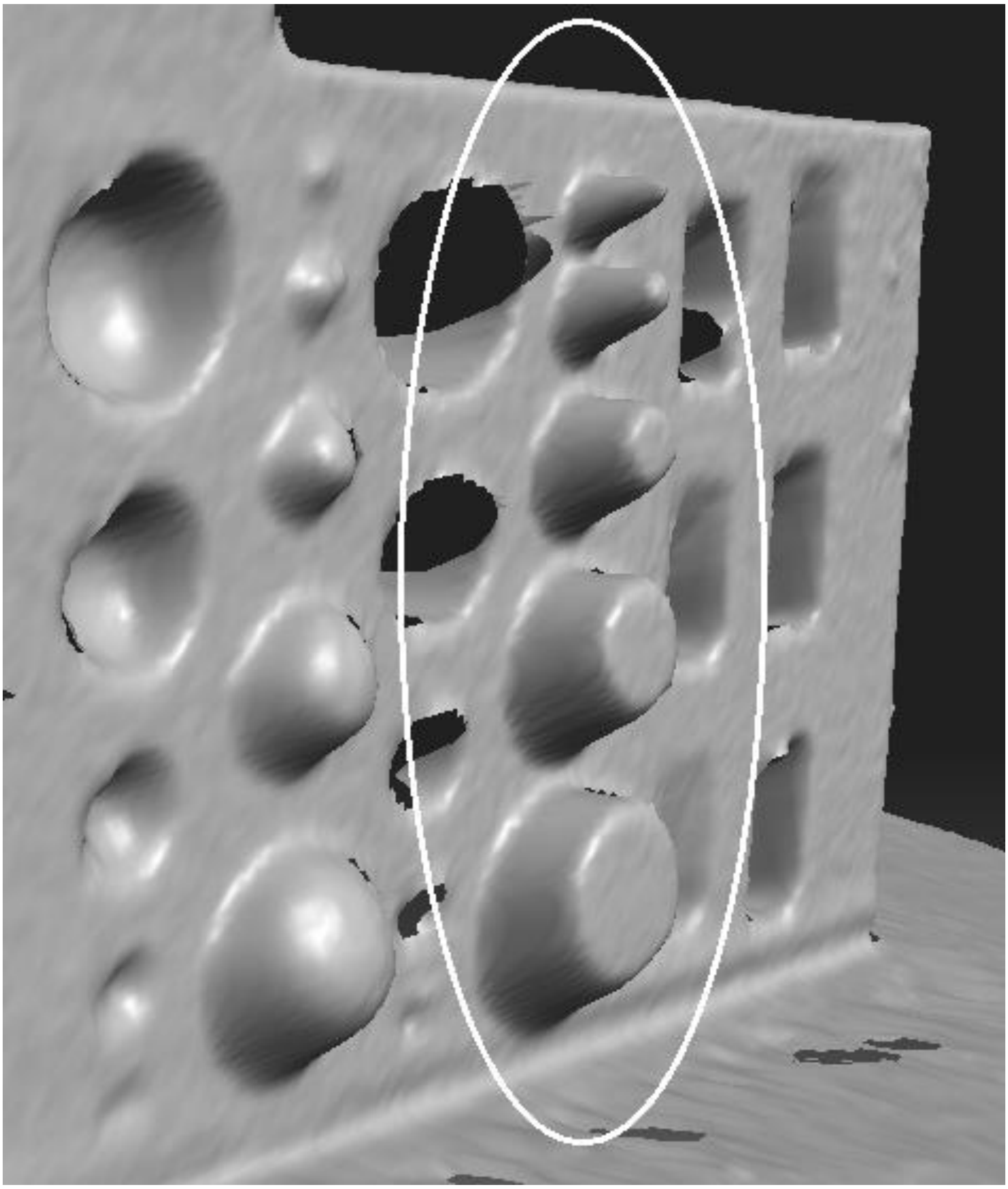


Figure 6.9. Improper Geometry Capture of Extruded Features using Structured Light

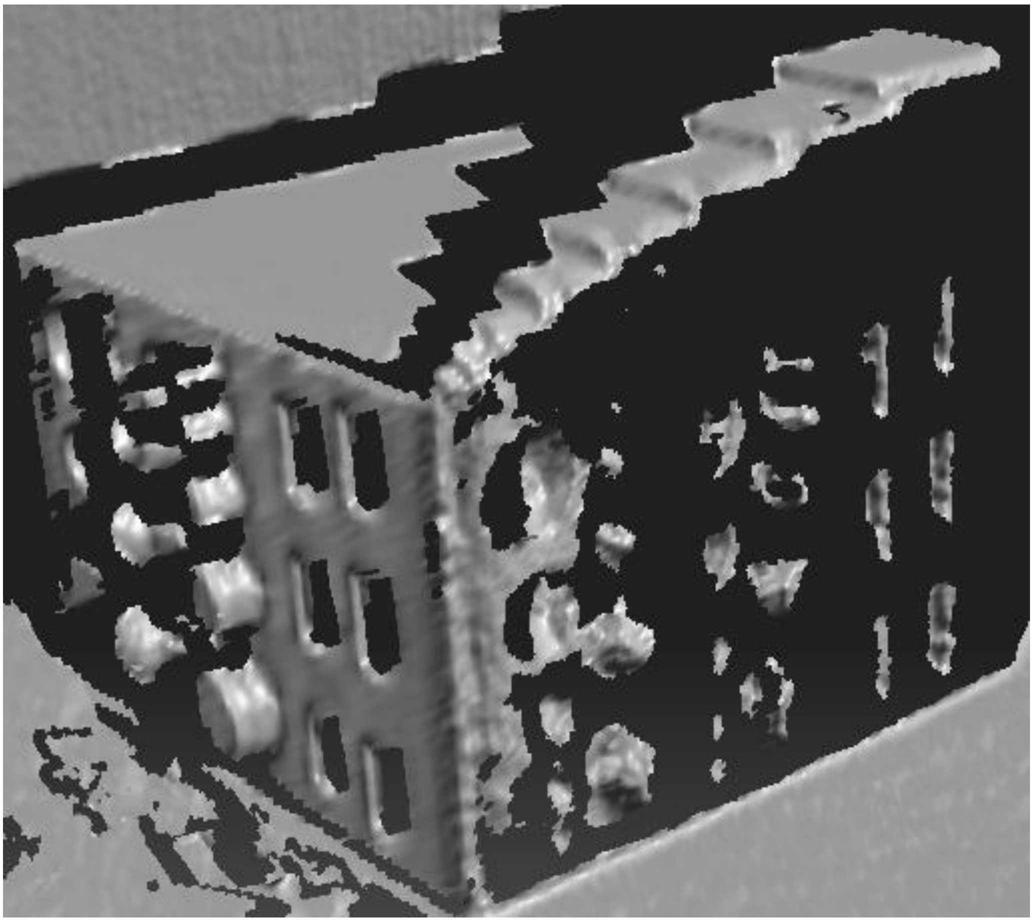


Figure 6.10. Difficulties of Scanning Features of a Black Reflective Surface using Structured Light

Once the scans were aligned as best as possible, they were fused together to give a single 3D file in the form of an *.obj (Figure 6.11). SolidWorks limits the *.stl file size to files with less than 20,000 triangular facets making up the mesh [72].

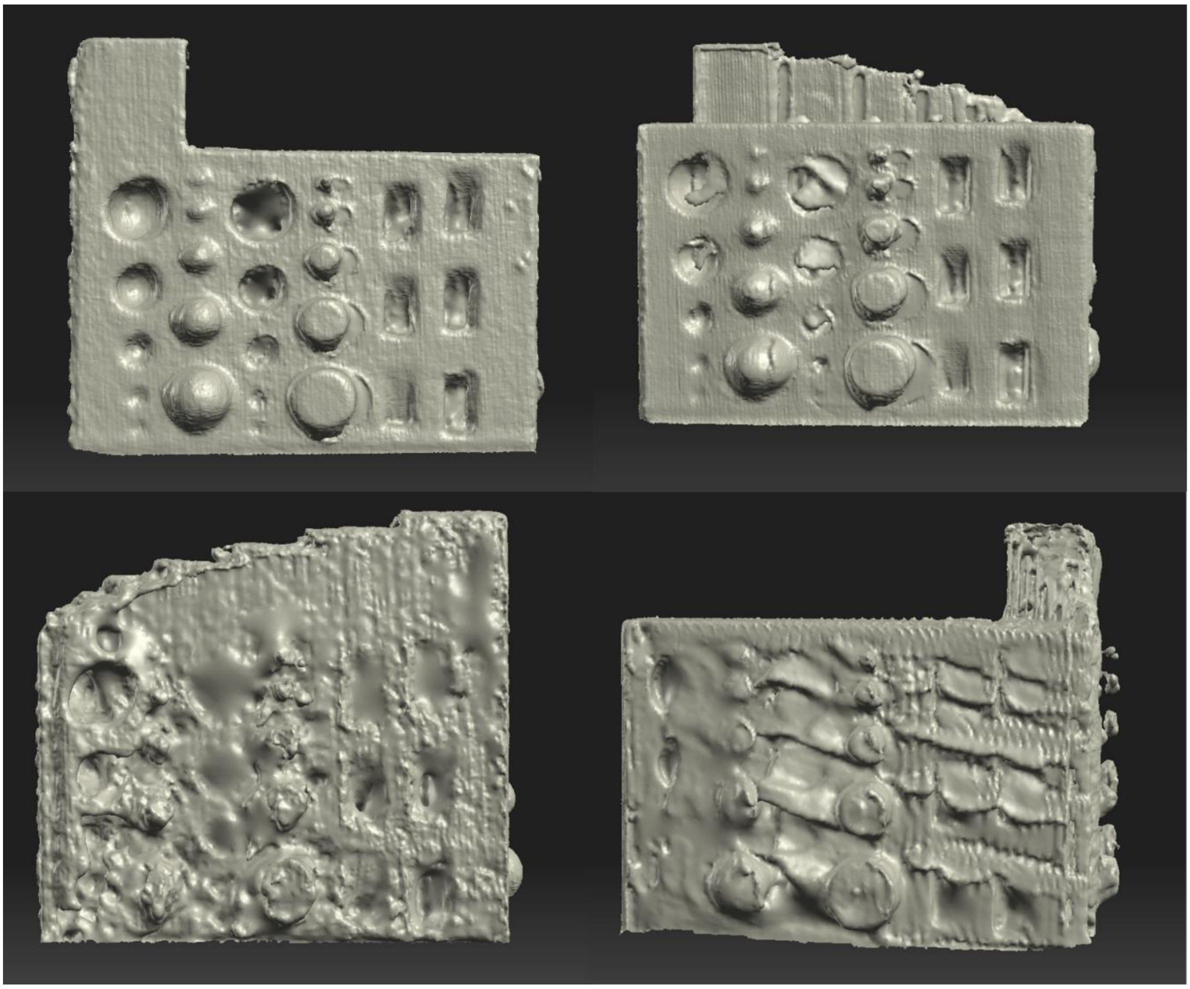
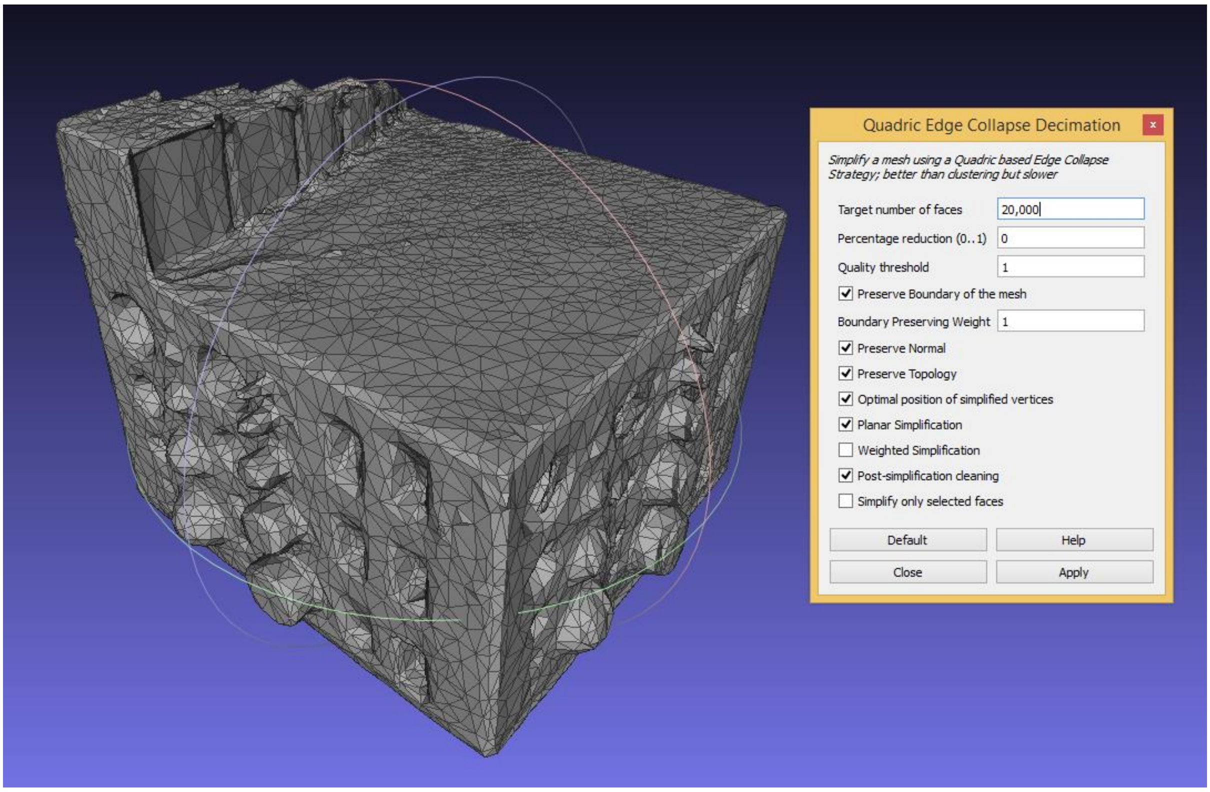


Figure 6.11. Fused David Laserscanner Scan Result

The fused scan was too large to directly import into SolidWorks so it was imported to MeshLab to be simplified. The command ‘Quadric Edge Collapse Decimation’ was used, which allows the user to determine the target number of facets that the mesh is to be reduced to 20,000 in this case (Figure 6.12).



Simplify a mesh using a Quadric based Edge Collapse Strategy; better than clustering but slower

Target number of faces: 20,000
Percentage reduction (0..1): 0
Quality threshold: 1
☑ Preserve Boundary of the mesh
Boundary Preserving Weight: 1
☑ Preserve Normal
☑ Preserve Topology
☑ Optimal position of simplified vertices
☑ Planar Simplification
☐ Weighted Simplification
☑ Post-simplification cleaning
☐ Simplify only selected faces

Figure 6.12. Simplified Test Cube Mesh using 'Quadric Edge Collapse Decimation'

Once the mesh was below 20,000 facets it could then be imported into SolidWorks for comparison against the original model (Figure 6.13). The overall dimensions of the geometry captured was accurate to less than 1mm at some points (Figure 6.14), though this is highly dependent on how well the scans have been stitched together. The disadvantage of having to simplify the model to such a low number of faces is that a great amount of detail is lost. The single fused scan consisted of over 80,000 faces compared to the simplified mesh reduction to 20,000. This means that the comparison shown in Figure 6.13 is not as accurate as it could have been had SolidWorks been capable of handling a larger mesh size. It is possible to import larger *.stl files as ‘graphic features’ though these cannot be moved or rotated into position, and do not show the mesh, which makes for a poor comparison.

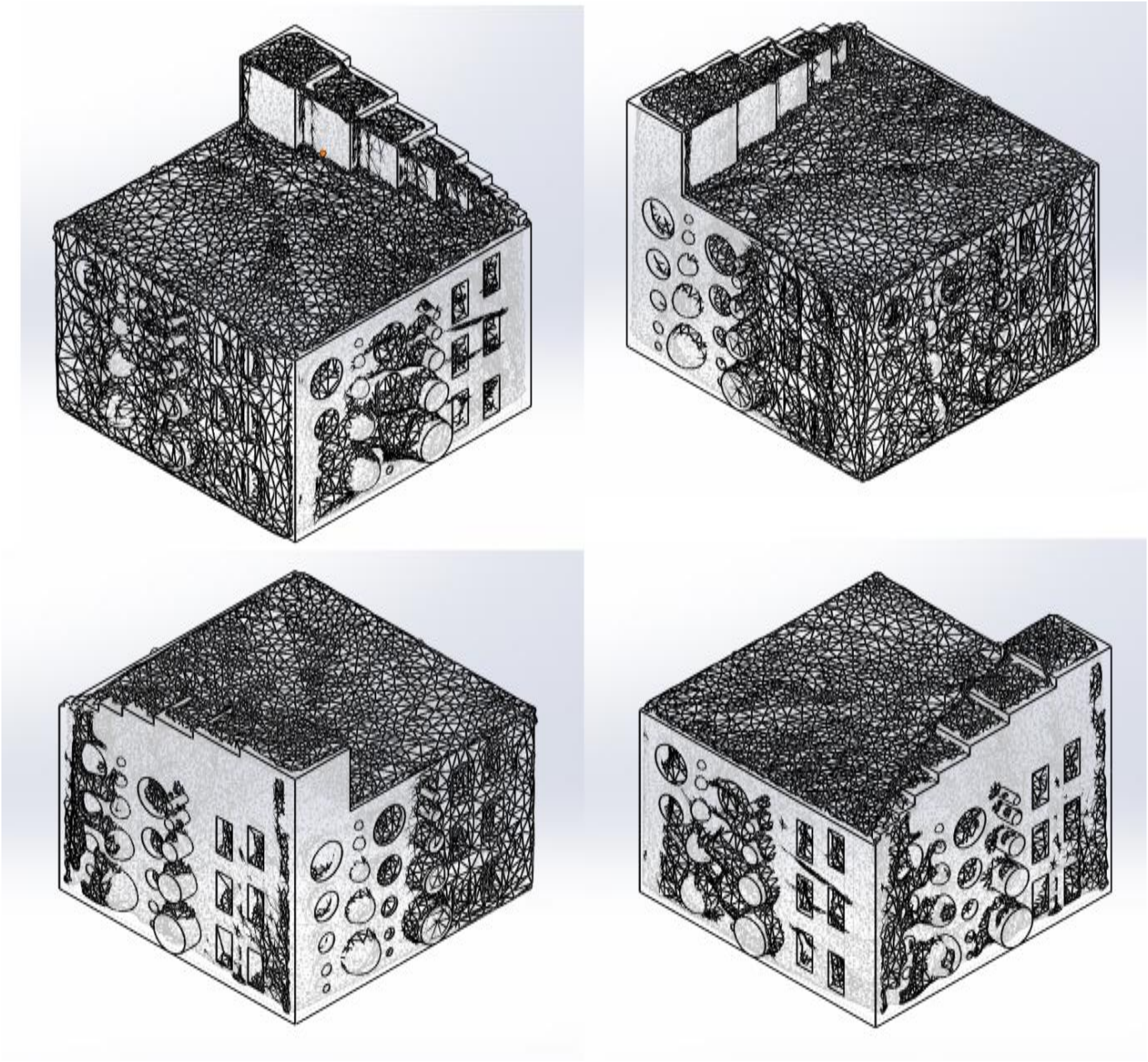


Figure 6.13. Structured Light Comparison with Original SolidWorks Model

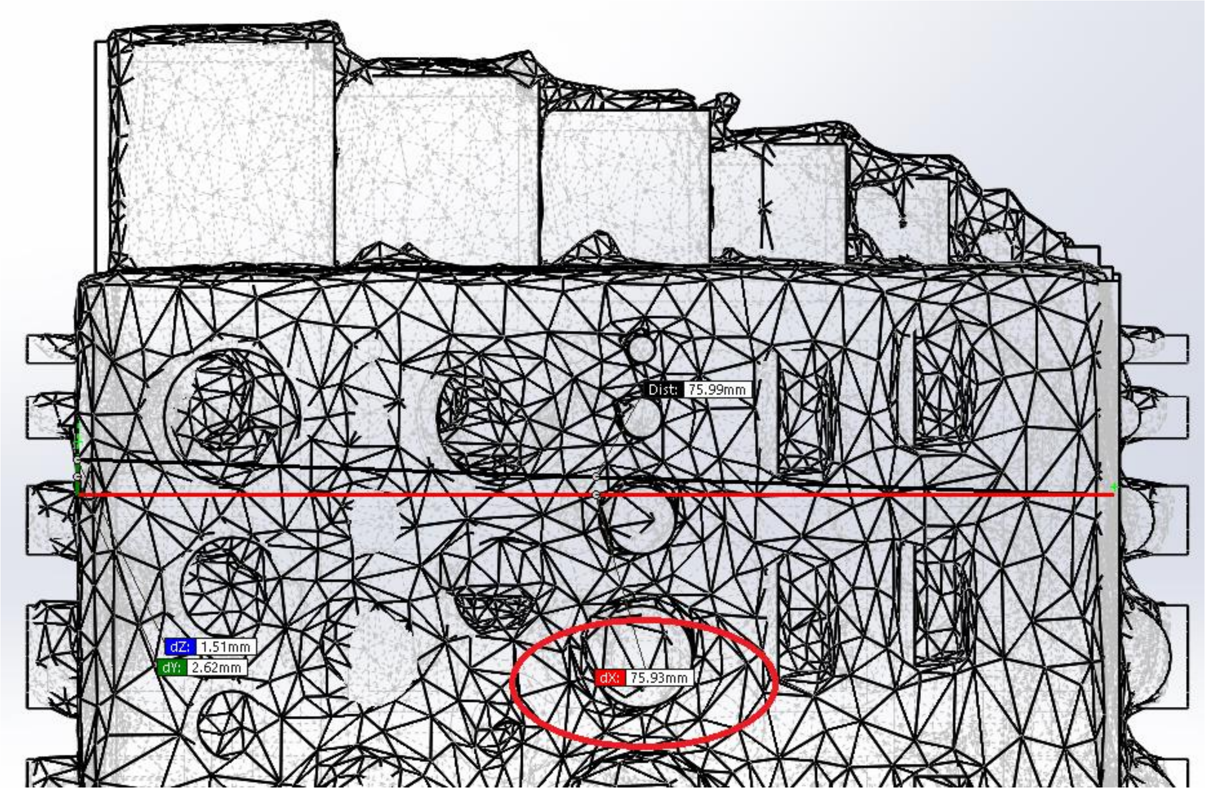


Figure 6.14. Dimensional Accuracy of Structured Light Scanner

6.2. Handheld IR Scanner

The 3D Sense by Cubify was used once again, as mentioned previously in Chapter 5.4. The test cube was placed on a flat surface and the scanner was moved around it to capture it in a 3D model, shown in Figure 6.15. Unlike the structured light scanning, the Sense is capable of producing a 3D model in one scan, rather than the multiple scans having to be stitched together as before. It is clear that the scan is whole and it has captured the features on each face to some extent. The Sense outputs an *.obj file, which can imported to MeshLab, then exported as a *.stl to be imported into SolidWorks (Figure 6.16). SolidWorks can only import simple *.stl files, if there are too many triangles in the mesh then alternative means must be used as with the structured light scan. Fortunately the Sense outputs a simple enough geometry that can be directly imported by SolidWorks. This will allow a comparison of the scanned geometry against the original model.

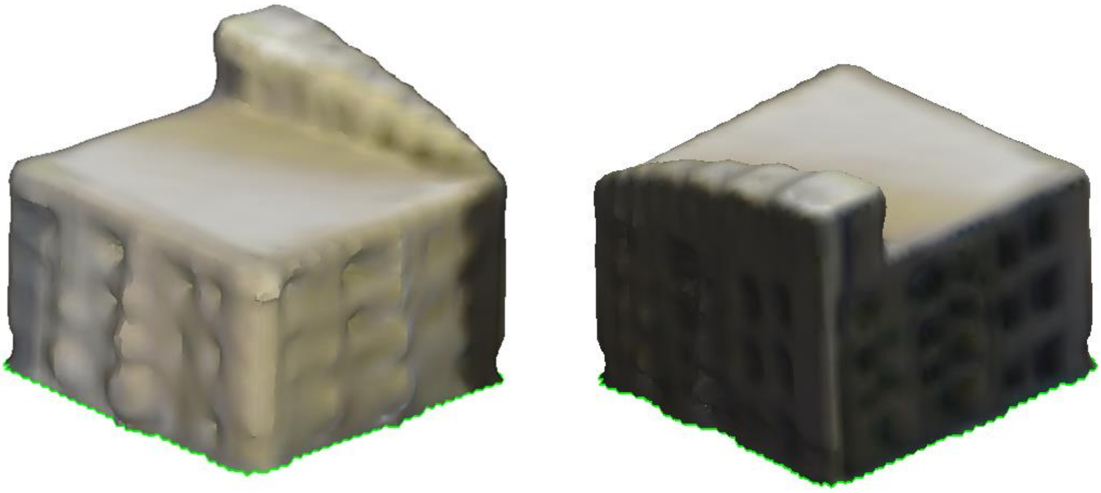


Figure 6.15. Sense 3D Scanner Test Cube Scan Results

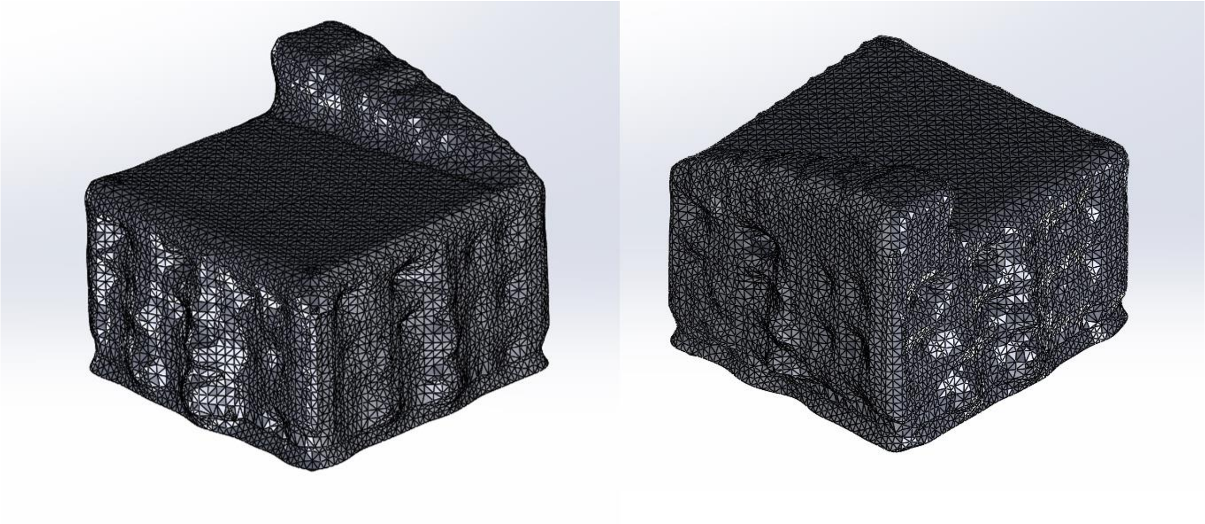


Figure 6.16. Sense Geometry Imported into Solidworks

By using the FeatureWorks option in SolidWorks, the imported geometry is checked for standard features such as holes, extrusions, drafts, revolves, ribs and fillets/chamfers. However the geometry has to be relatively simple and the scan must be a high quality representation of the geometry otherwise FeatureWorks will not be able to extrapolate features from a chaotic scan. Because the features captured by the Sense are not particularly clear, a solid model could not be made. Though the STL file can still be overlaid with the original SolidWorks model for a comparison (Figure 6.17).

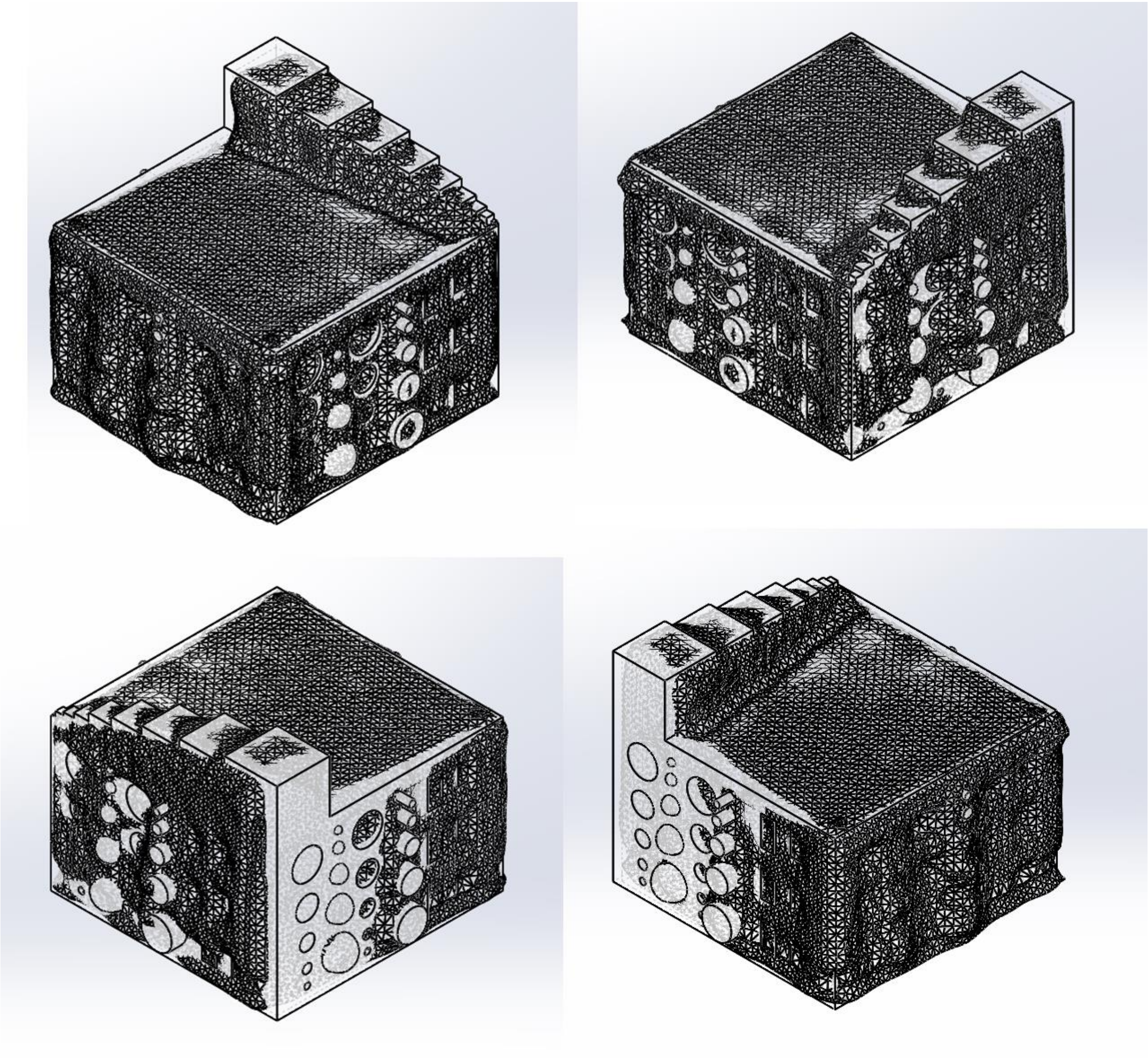


Figure 6.17. Sense Geometry Comparison with Original SolidWorks Model

This shows that the Sense scanner did not accurately scan any of the features clearly. It coped better with larger features, though they are more like ‘blobs’ than distinguishable extrusions or holes, though it should be said that it coped better on the matte surfaces than on the reflective ones. A few attempts at scanning the test cube had to be carried out to gain a complete model, as it struggled in particular with the black reflective features.

Given that the Sense was scanning features on its smallest object setting, it would stand to reason that it is a capable scanner, though it has limitations in terms of its accuracy when features become smaller than 10mm. Its technical specification sheet states it is capable of a spatial resolution of 0.9mm at a distance of 0.5m, and a depth resolution of 1mm at a the same distance. It is one of the cheapest scanners to be found currently however, at a price of £279 [73].

6.3. Scanner Conclusions

The Sense is not capable of producing a 3D scanned geometry of sufficient detail for use in reverse engineering purposes unless the part to be scanned has a minimum feature size of over 10mm. it is somewhat affected by the reflectivity of the object to be scanned though it is fully proficient to capture parts of differing colours. It was not determined how well it can cope with specific features such as holes and angled recesses, due to it not being able to capture the level of detail presented by the test cube.

The Structured light method using the David Laserscanner software worked better than the Sense for capturing the features. It is however considerably more of an effort involved in producing the final digital 3D model given that it produces a series of scans to be stitched together. In this process it is also imperfect as any misalignment form multiple scans can distort the final fused model. The more individual scans that comprise the fused scan, the more this misalignment is averaged out, however this can cost the accuracy of the features represented.

7. Discussion & Conclusions

The accessibility of desktop 3D printers has allowed people with limited engineering knowledge to gain access to the AM industry. Their ease of use allows hobbyists as well as technical persons to create models, and even functional mechanical parts for systems. This means there is scope for using them in manufacturing processes, as is done already in many casting techniques. Thus if a person requires a replacement component for a system, then it is possible for the manufacturing of this part using these cheap AM methods, reducing any costs implied in its manufacture. However, when reverse engineering a part for manufacture, it is required to somehow digitise the geometry into a 3D computer model, from which it can be manipulated as required, be it for minor design changes or correction on damaged or missing sections. AM techniques may have become more accessible but methods of scanning in part geometry have not. The cost of 3D printers has reduced and the quality that they are capable of producing is getting better all the time. It would seem however that whilst there are cheap scanners available, they have not improved at the same rate as the AM techniques. It is possible to gain 3D models by using them though they are no way near comparable to their more costly options in terms of quality of the 3D models produced.

The case study in particular that proves this point, as explored in this thesis, is that of the 7lb Uno coffee roaster drum pulley wheel. It presented a damaged pulley wheel, which was a modified version of the original. Thus it provided the required dimensions of the pulley, though not its geometry feature of the internal spokes, given that it was just a welded flat plate, replacing the original part for the system. To gain the original spoke features, a larger version of the pulley was available to digitise into a 3D CAD model and be scaled to the correct dimensions. This presented difficulty however as the 3D scanners which were available for use could not capture the geometry fully or with sufficient accuracy to be able to use in a CAD software, thus an alternative geometry collection method had to be used.

A successful CAD model was created, though it was undertaken using a combination of manual measurements as well as tracing a photo on 3D modelling software SolidWorks. It enabled a pattern for sandcasting to be designed and fabricated using an FDM machine. This was used successfully in manufacturing a cast metal pulley wheel with the desired internal spoke features. However, given build area constraints, the part was not at the required size for operation. Yet it did prove that a part can be manufactured with relative cost-effectiveness, with little technical experience. When creating the pattern, warping was an issue, given the residual stresses from the hot extruded plastic cooling. The method of fabrication also produces striation on the model as the layers are built up. Since the printed part was to be used as a pattern for casting, the striations were evident in the cast part. To overcome these issues a different AM method could be used such as SLA which is capable of a higher resolution print. It would incur a greater cost in terms of raw material though. The pattern originally incorporated the runners and risers of the mould cavity, though through a number of attempts it was realised that it was more effective to just create these by hand. The best design for a model and how it should be split, if it should incorporate runners and riser in the printed pattern, etc. is entirely dependent on the geometry of the part to be produced, in the instance of the pulley wheel a number of failures resulted in the realisation of the methods used. This is inclusive of the method of AM used, as sand casting normally results in a rough surface which must be post processed after casting.

While the part which was manufactured was done so by using in-house machines available to the author in an engineering environment, and therefore not entirely available to an average person, it could be said that it is not as accessible as presented. However there are a number of ways to produce components without having to purchase a number of different machines. It is possible to obtain AM parts by using bureau services such as Shapeways. By doing so the only cost involved is that of the part and machine time, rather than buying a desktop printer for oneself. This would allow the ability to obtain a full scale model, which was a restricting factor on the pulley wheel. It would also be advantageous to get the same model made in a number of different materials, manufactured using different methods in order to determine the best models to use for the pattern for sandcasting. They could be compared against one another in terms of cost, finish and dimensional accuracy. Rental of 3D scanners to obtain the 3D geometry data would allow access to higher quality scanners, without the costs of purchasing a single unit. The downside of this though is that each time a component is to be reverse engineered or manufactured is that a new rental will have to be obtained, rather than being able to use a machine which is owned in-house. If it was apparent that there was going to be a high usage for the scanner, in which the cost of buying a more expensive, better quality scanner could be justified against any savings which might be met by its use in the RE process then it could be viable to invest in a better scanner rather than rent it.

It is the authors' opinion that both AM and 3D scanning have become much more accessible over recent years. AM in particular has been progressing rapidly in terms of the quality of parts produced from relatively cheap desktop printers. It can be said however that 3D scanners do not provide the same value for money with regards to the quality of scans created. They also require some technical experience in some software's to clean up any scans which are obtained. How well a more expensive scanner with dedicated software will perform is unknown. But as for the cheaper scanner, it took a substantial amount of time and effort to obtain any kind of workable 3D model, often with the use of multiple software programmes. Dedicated software and an improved scan result would likely make the transition of the scan to a 3D model much easier.

The case study on the Uno pulley wheel presented a geometry which did not contain any freeform surfaces, and so made it easier to model in SolidWorks. If an object was to be reverse engineered and it had freeform surfaces, then it would require 3D scanning equipment capable of accurately reproducing the geometry into a 3D model. While the structured light method used in Chapter 6 was capable of capturing an accurate scan, it required multiple scans to be stitched together to complete a 3D model. It did not do this very well with the software it used. A better quality scanning device would need to be used to capture a freeform surface and produce a complete 3D scan. As there is no way to manually measure a freeform surface to check model validity, as can be done with simpler geometries, it would be wiser to rely on a higher quality scanner.

Avenues which require further exploration is that of the direct printing of disposable moulds. There are a few examples of this in Chapter 5.7, though it would need an investigation into the capabilities of this application such as its ability to produce certain features as well as the level of detail and accuracy possible using this technique. Although it does drastically reduce the time for forming a mould to casting a part, it does have limitations. However, for use in reverse engineering it could become a powerful method of manufacturing parts. A scanned 3D model of the component could be used to create a data file of a negative (i.e. the mould), then fabricated using this method. The part could then be cast and produced quickly with the potential for minimal cost. Further investigation into its time and cost saving versus traditional investment casting methods would be required to determine if it would be a viable route for the future of industry to consider.

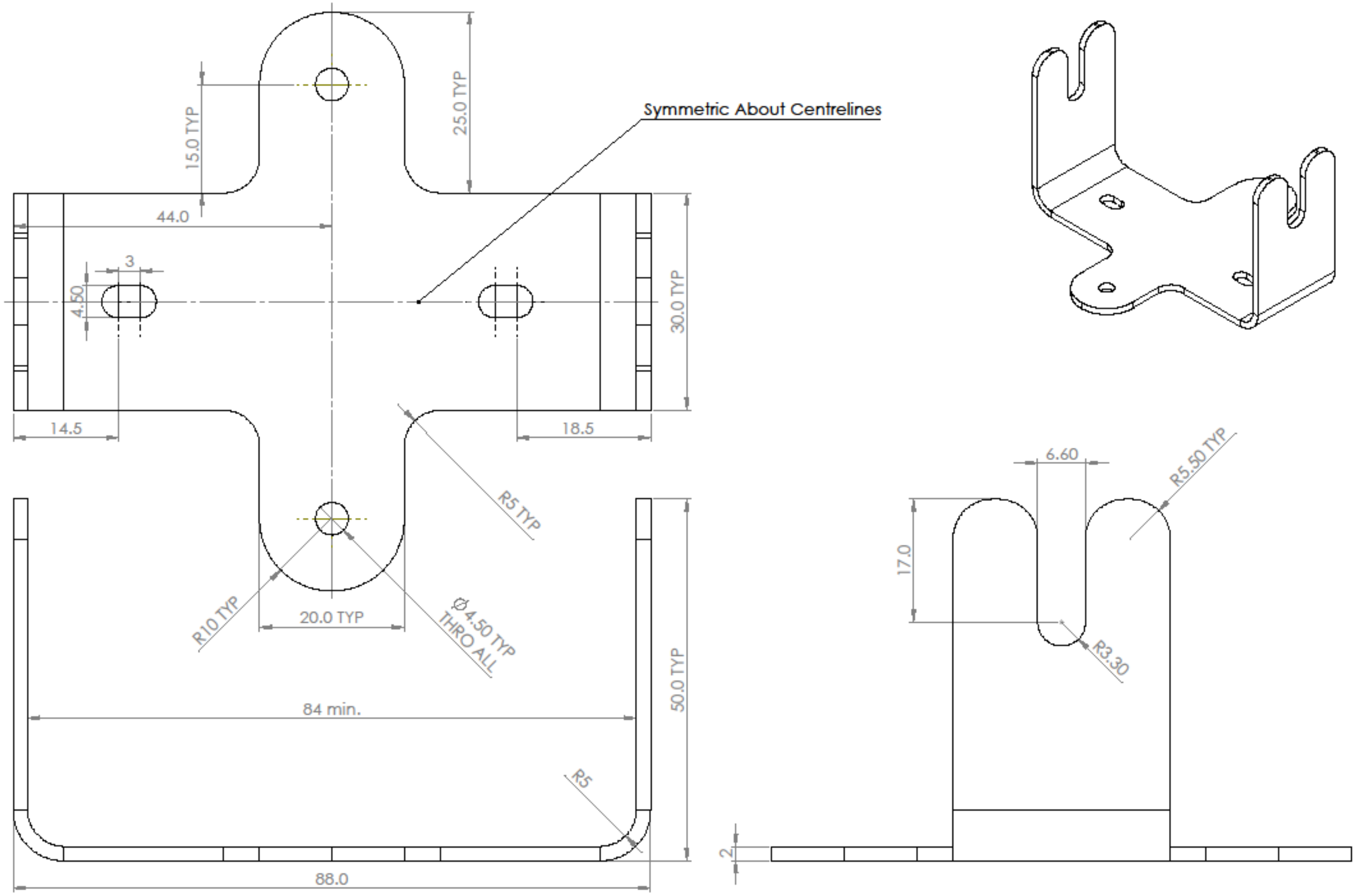
In general, it was determined that it is entirely possible to reverse engineer a component and manufacture it using AM methods. Though the level of quality of some of the processes is varied, especially geometry capture methods when reverse engineering from a physical object to a 3D computer model. The only real limitation is the cost, there are better AM machines and higher quality scanner available than what was used to manufacture the Uno pulley wheel, however they can be considerably costly and the use of them would outweigh any financial benefits gained by using cheaper options. When that is the case, the part may as well be manufactured using traditional methods, as the only saving would be on time. At which point it would be up to a business or individual to determine the preference over time or cost saving measures.

8. Appendices

8.1. List of Parts

Part Number	**Part Name**	**Quantity**
ATK001	Bracket	1
ATK002	Shaft	1
ATK003	Pulley	2
ATK004	Drum Tab	1
ATK005	Uno Pulley Wheel	1
ATK006	Tray Frame Sheet Metal	1
ATK007	Tray Mesh	1
ATK008	Top Tray	1
ATK009	0.75 Inch Axle	1
ATK010	0.625 Inch Axle	1
ATK011	6900-ZZ Bearing	2
ATK012	Internal Cirlcip 23mm	2
ATK013	External Circlip 10mm	2

8.2. Uno Coffee Roaster Drawings for Manufacture



Note: All sharp edges removed and holes deburred

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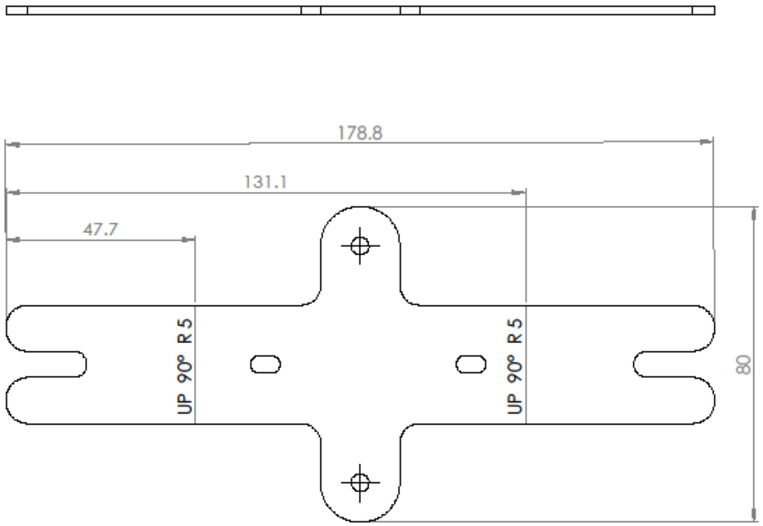

Sheet Metal Drawing of Bracket Part ATK001

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MATERIAL: Mild Steel

REVISION: D

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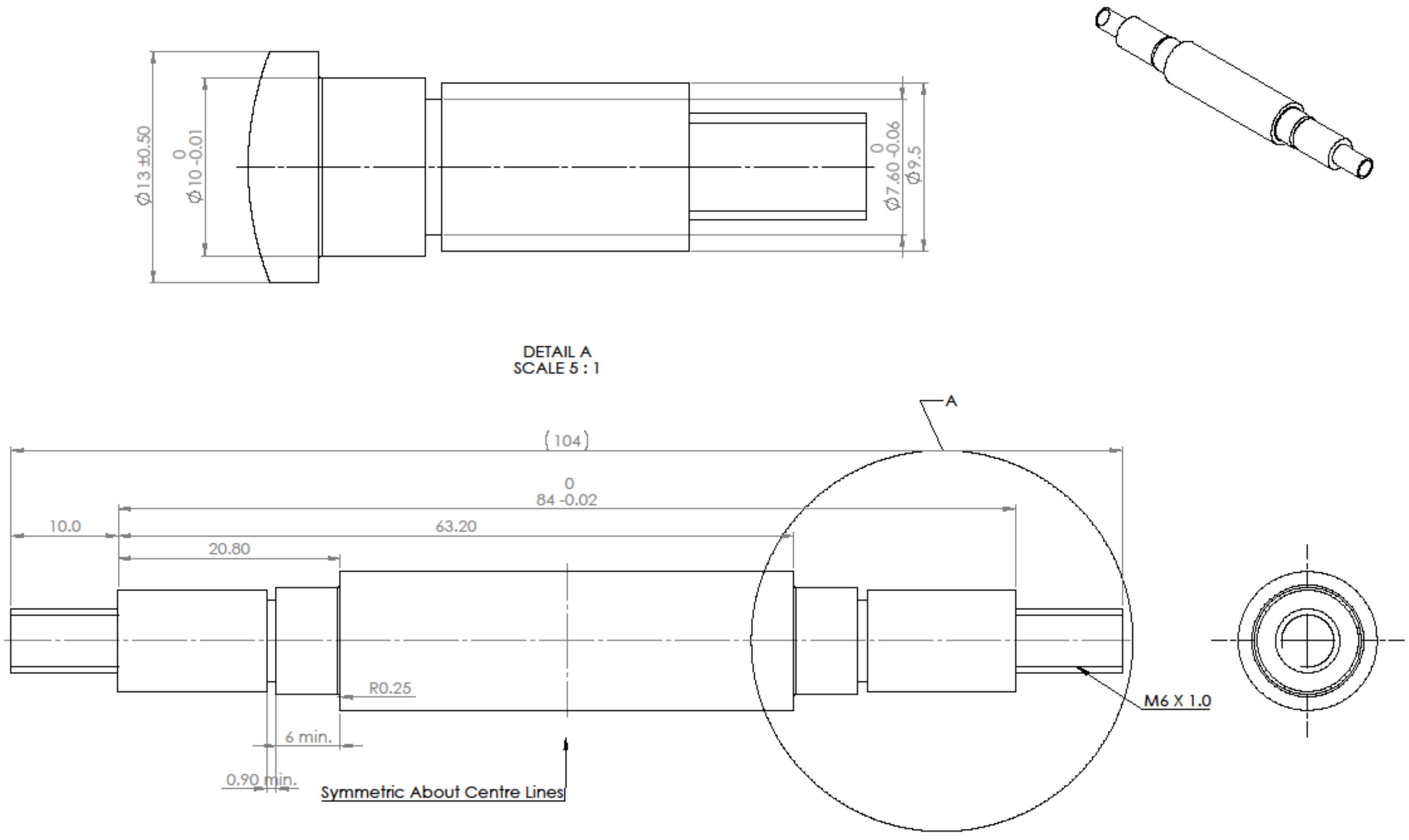

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PART NAME: Shaft

MATERIAL: Stainless Steel 316

PART NUMBER: ATK002

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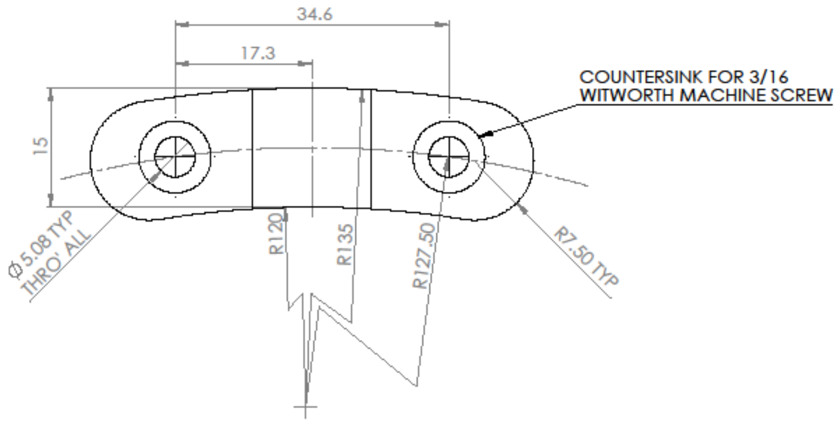

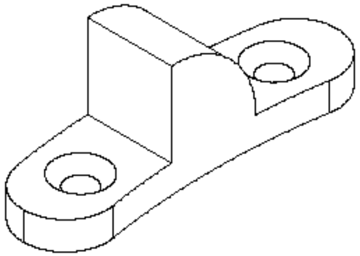

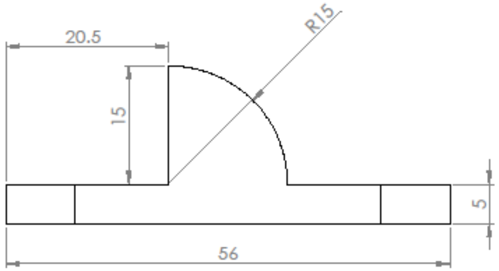

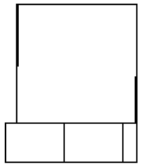

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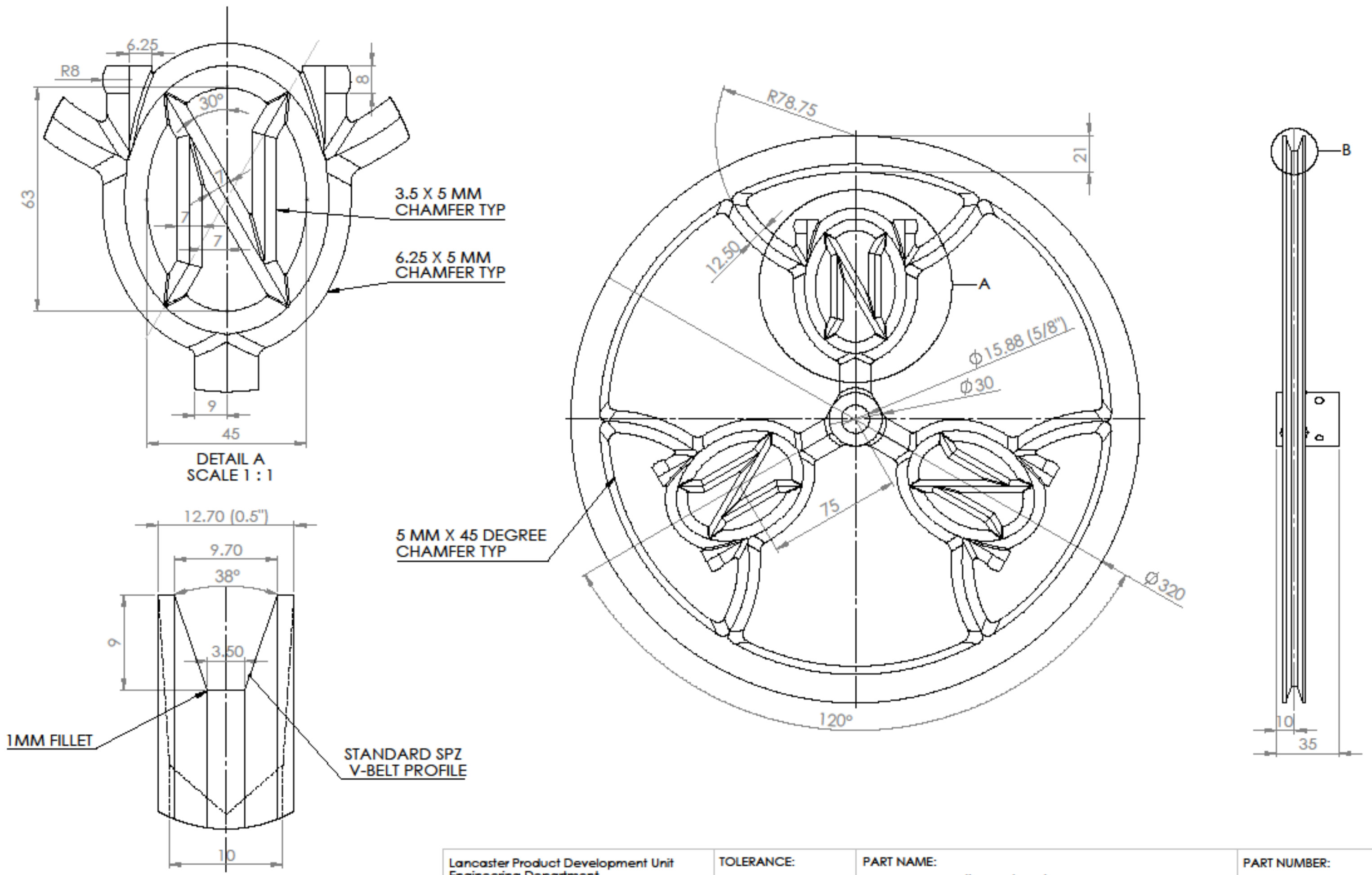

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PART NAME: Uno Pulley Wheel

MATERIAL: Mild Steel

PART NUMBER: ATK005

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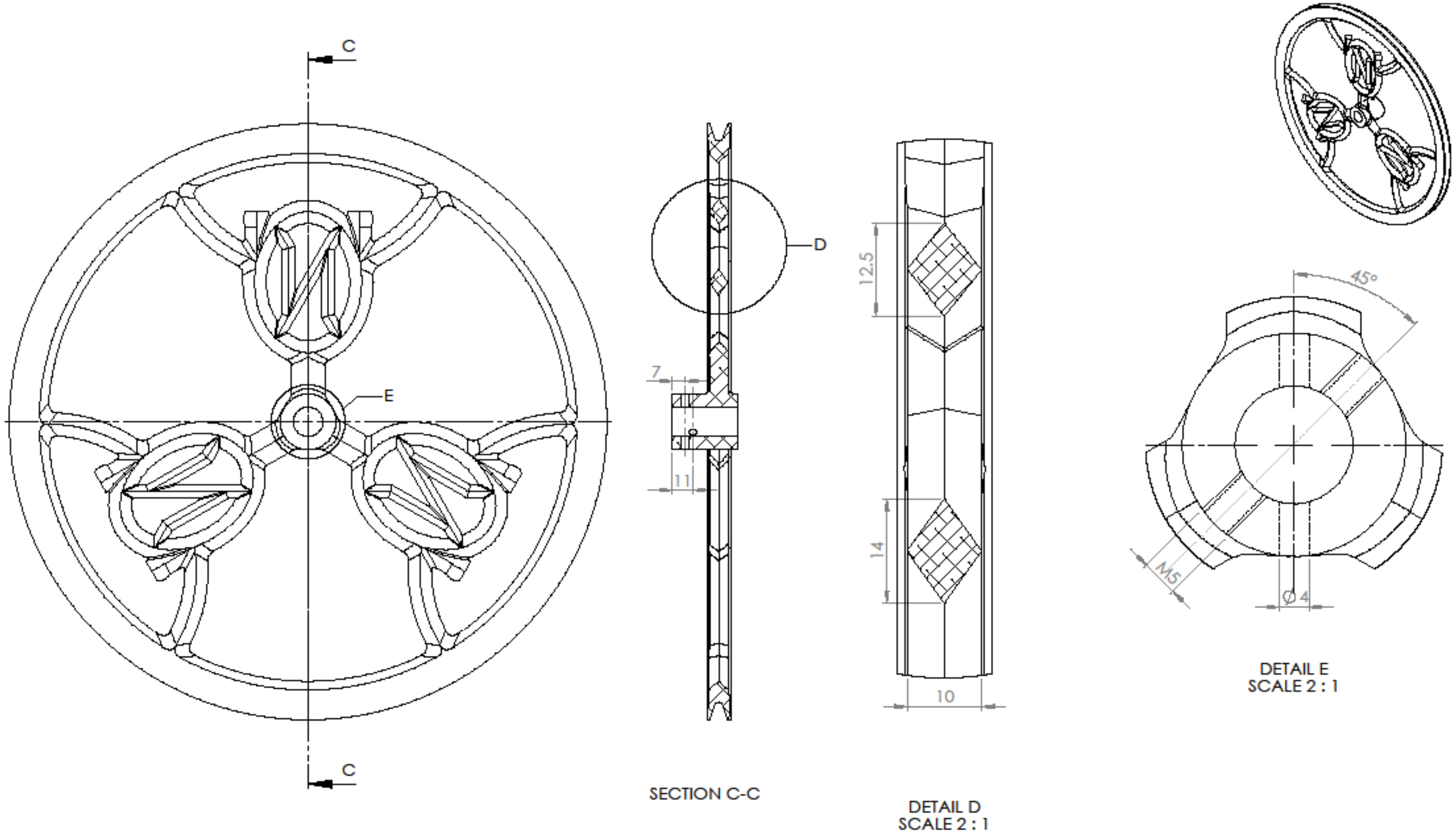

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(.00x): ±0.005
(.000x): ±0.0005
UNLESS OTHERWISE STATED

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MATERIAL: Mild Steel

PART NUMBER: ATK005

REVISION: A

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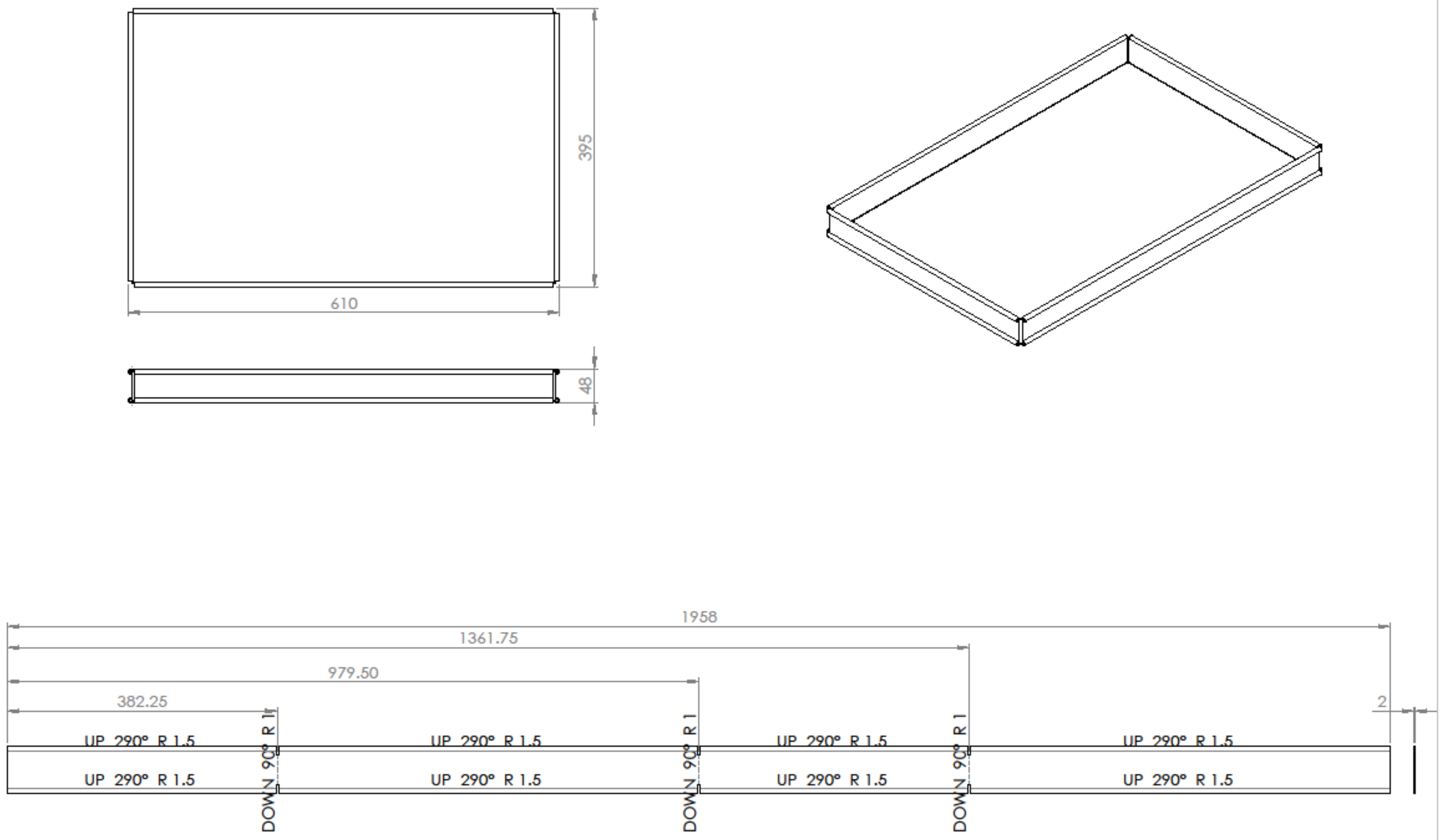

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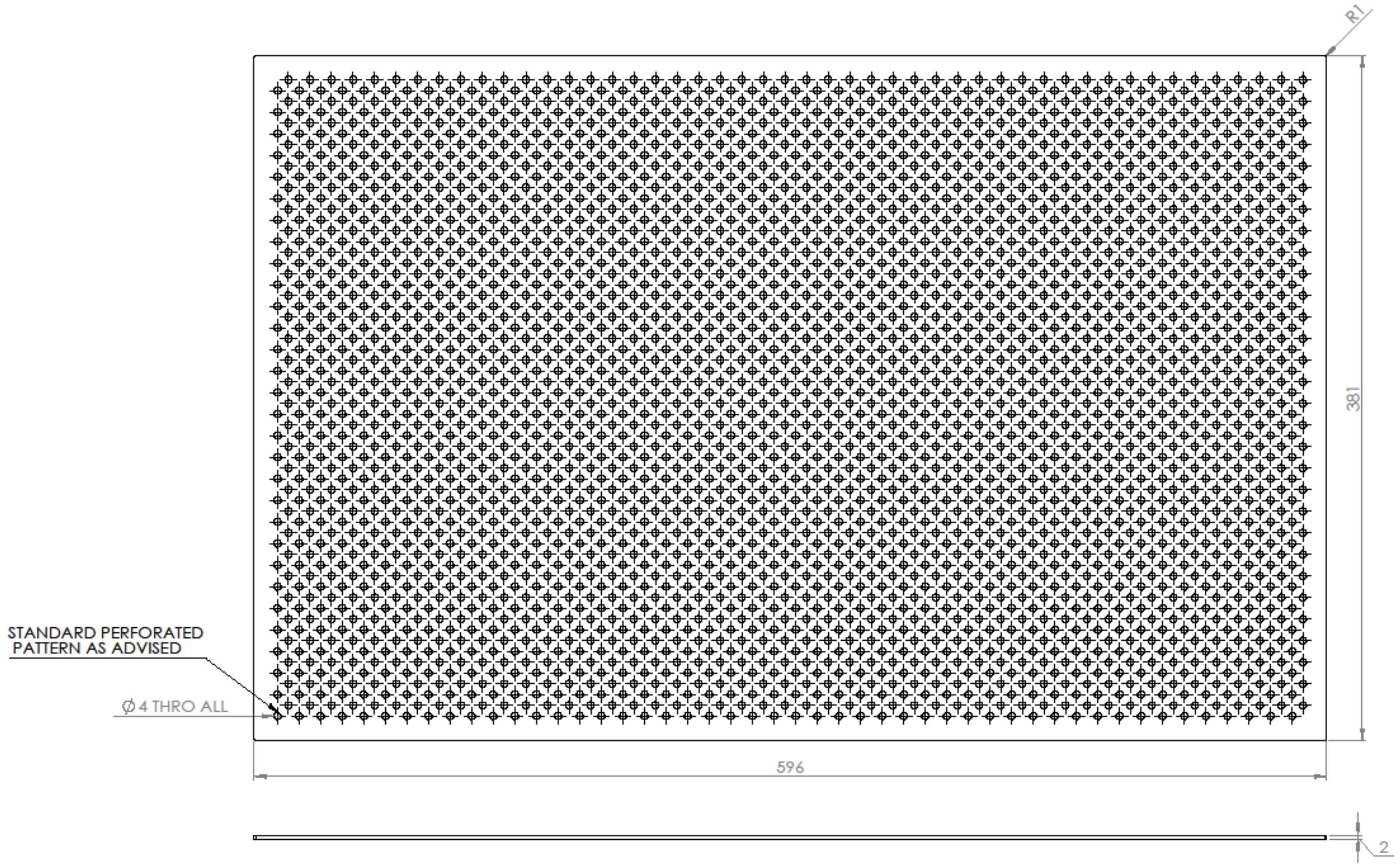
ALL DIMENSIONS IN MM	3RD ANGLE			



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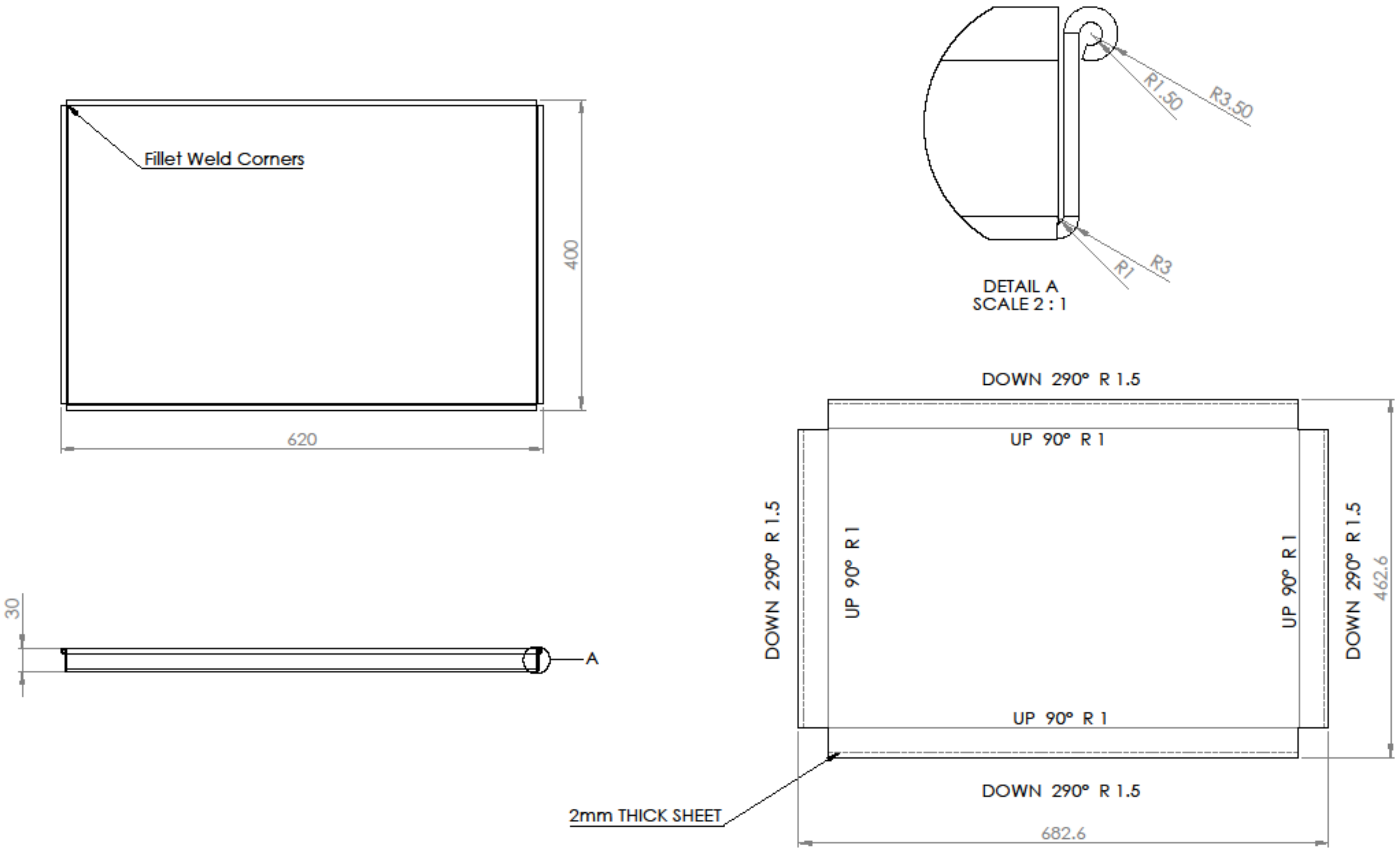
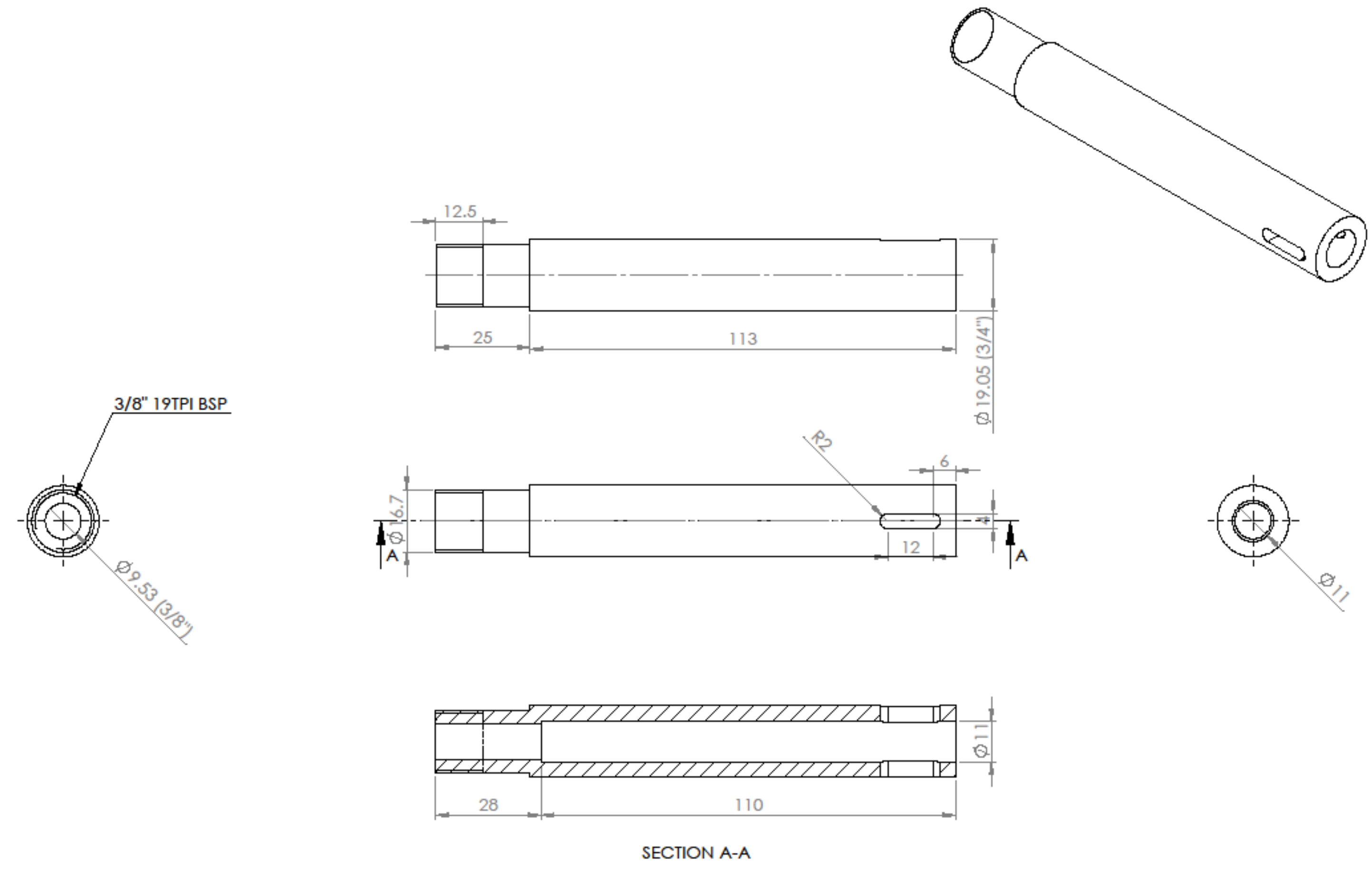
ALL DIMENSIONS IN MM	3RD ANGLE		

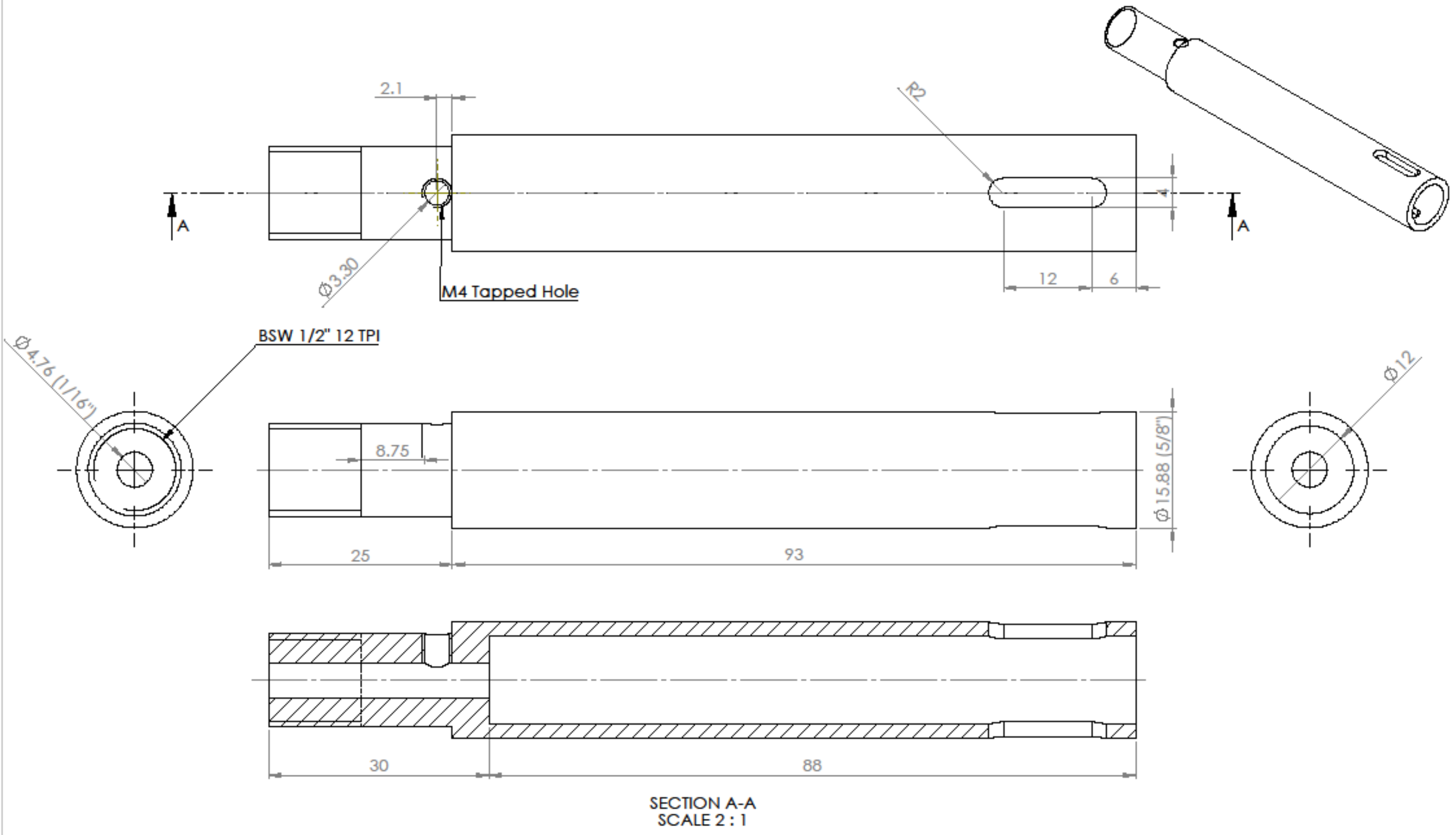


		Lancaster Product Development Unit Engineering Department Lancaster University Lancaster LA1 4YR T - (01524) 592 203 W - www.lpdu.lancs.ac.uk	TOLERANCE: (.x): ±0.2 (.0x): ±0.01 (.00x): ±0.005 (.000x): ±0.0005	PART NAME: Top Tray		PART NUMBER: ATK008
				MATERIAL: Mild Steel		REVISION: A
DRAWN DATE: 25/02/2015	DRAWN BY: CM	CHECKED BY: JR	UNLESS OTHERWISE STATED	DO NOT SCALE	ALL DIMENSIONS IN MM	3RD ANGLE



Lancaster Product Development Unit Engineering Department Lancaster University Lancaster LA1 4YR T - (01524) 592 203 W - www.lpdu.lancs.ac.uk	TOLERANCE: (.x): ±0.2 (.0x): ±0.01 (.00x): ±0.005 (.000x): ±0.0005 UNLESS OTHERWISE STATED	PART NAME: 0.75 inch Axle	PART NUMBER: ATK009
		MATERIAL: Stainless Steel 316, 3/4" Bar 3/16" Wall thickness	REVISION: A

DRAWN DATE: 25/02/2015	DRAWN BY: CM	CHECKED BY: JR	DO NOT SCALE	ALL DIMENSIONS IN MM	3RD ANGLE



Lancaster Product Development Unit Engineering Department Lancaster University Lancaster LA1 4YR T - (01524) 592 203 W - www.lpdu.lancs.ac.uk	TOLERANCE: (.x): ±0.2 (.0x): ±0.01 (.00x): ±0.005 (.000x): ±0.0005	PART NAME: 0.625 inch Axle	PART NUMBER: ATK010
		MATERIAL: Stainless Steel 316, 5/8" Bar 9/32" Wall Thickness	REVISION: A

DRAWN DATE: 25/02/2015	DRAWN BY: CM	CHECKED BY: JR	UNLESS OTHERWISE STATED	DO NOT SCALE	ALL DIMENSIONS IN MM	3RD ANGLE

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