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SHORT COMMUNICATION

Computer-aided Reverse Engineering for Rapid Replacement of Parts

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ABSTRACT

Indigenous product development using conventional means involves a relatively long lead time and cost, especially for replacing worn out and broken parts. This paper presents methodologies and technologies for computer-aided reverse engineering, illustrated by a real-life case study of an aluminium alloy separator body of a hydraulic filter assembly for the special army vehicle. It involved reconstruction of part geometry using 3-D scanning, material identification using spectrometry, casting process optimisation using simulation software, and fabrication of prototype and tooling using rapid prototyping systems. It was found that the fabrication of wax patterns directly from reverse-engineered CAD data in a suitable rapid prototyping system (such as thermojet), followed by conventional investment casting, gives a reliable and economic route for rapid development of one-off intricate parts for the replacement purpose.

Keywords: Computer-aided design, metal casting, process simulation, rapid prototyping, reverse engineering, solid modelling, spectrometry

1. INTRODUCTION

Engineering products, including those developed in defence establishments, can be broadly classified as new parts designed for a fresh set of functional requirements, modified parts for improved performance, manufacturability, etc, and replacement and spare parts such as for broken and worn out items. Development of new as well as replacement parts is becoming difficult owing to the ever-increasing shape complexity, performance requirements, and pressure to complete the activity faster.

1.1 Indigenisation

The practice of indigenisation in the defence sector typically follows these steps. After the receipt

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of a sample part, its dimensions are measured and its 2-D drawings are prepared, which takes 2-3 months for parts with medium complexity. A tender enquiry is then floated for inviting potential vendors on competitive basis. The selected vendor may take 6-12 months for developing the tooling and establishing the manufacturing process to produce the first batch of sample parts. These are subjected to inspection and testing procedures before acceptance of the sample.

1.2 Indigenisation/Import

An easier and faster option in the short run is to import the part or the underlying technology. Imports, however, involve loss of foreign exchange, possible continuance of dependency, and delay in procurement and shipment. Technology transfer may make one becoming self-reliant over a period, but is usually not feasible for one or two parts, and its success depends on political-economic relations and trust between the two countries. In contrast, indigenous development requires strong determination to overcome technological and time constraints, including integration and collaboration of technologies across the country. It, however, eventually leads to self-reliance, employment generation in the country, and potential revenue generation by its exports in future.

1.3 Product Development

Over the past few years, several new methodologies and technologies have emerged to streamline and speed up the product development activities. These include computer-aided design (CAD), computer-aided engineering (CAE), computer-aided manufacturing (CAM), rapid prototyping (RP), and rapid tooling (RT). The availability of a large pool of engineers with software skills in the country, and worldwide recognition of their capabilities has prompted many multinational companies to establish their R&D centres in India. As the experience of such engineers gradually diffuses into local establishments and industry, indigenous product development is bound to accelerate.

The jump from the old era of imports and technology transfer, into the new age of rapid product development, can be cushioned by starting with the development of existing parts (for replacement purposes) and their modification (for improved performance or manufacturability) using computer-aided technologies. This is broadly referred to as computer-aided reverse engineering.

The paper presents a brief overview of reverse engineering, including techniques for obtaining the part geometry, identifying its material, and rapid manufacturing techniques. In particular, the focus is on CAD/CAE/CAM and RP/RT technologies that can significantly speed up the development of metal castings. The primary aim of the experimental investigations reported here is to establish a suitable route for reverse engineering of metal castings required one-off or in small numbers at short notice.

A real-life case study of a separator body of a hydraulic filter assembly was takenup to validate the route and share the experience gained in using the above technologies.

2. COMPUTER-AIDED REVERSE ENGINEERING

Reverse engineering originally emerged as the answer to provide spares for replacing broken or worn out parts for which no technical data was available. This can be the case if the part was originally imported (without drawings) or the drawings being misplaced or lost. Re-engineering or reverse engineering such parts can be a less expensive option compared to re-importing, not only for immediate replacement, but also to create additional spares to maintain the product over a longer period.

Reverse engineering has been defined as a process for obtaining the technical data of a critical spare component[1]. Computer-aided reverse engineering relies on the use of computer-aided tools for obtaining the part geometry, identifying its material, improving the design, tooling fabrication, manufacturing planning, and physical realisation (Fig. 1). A solid model of the part is the backbone for computer-aided reverse engineering. The model data can be exported from or imported into CAD/CAE/CAM systems using standard formats such as IGES, STL, VDA, and STEP. The three most important sets of data in reverse engineering activities relate to the CAD

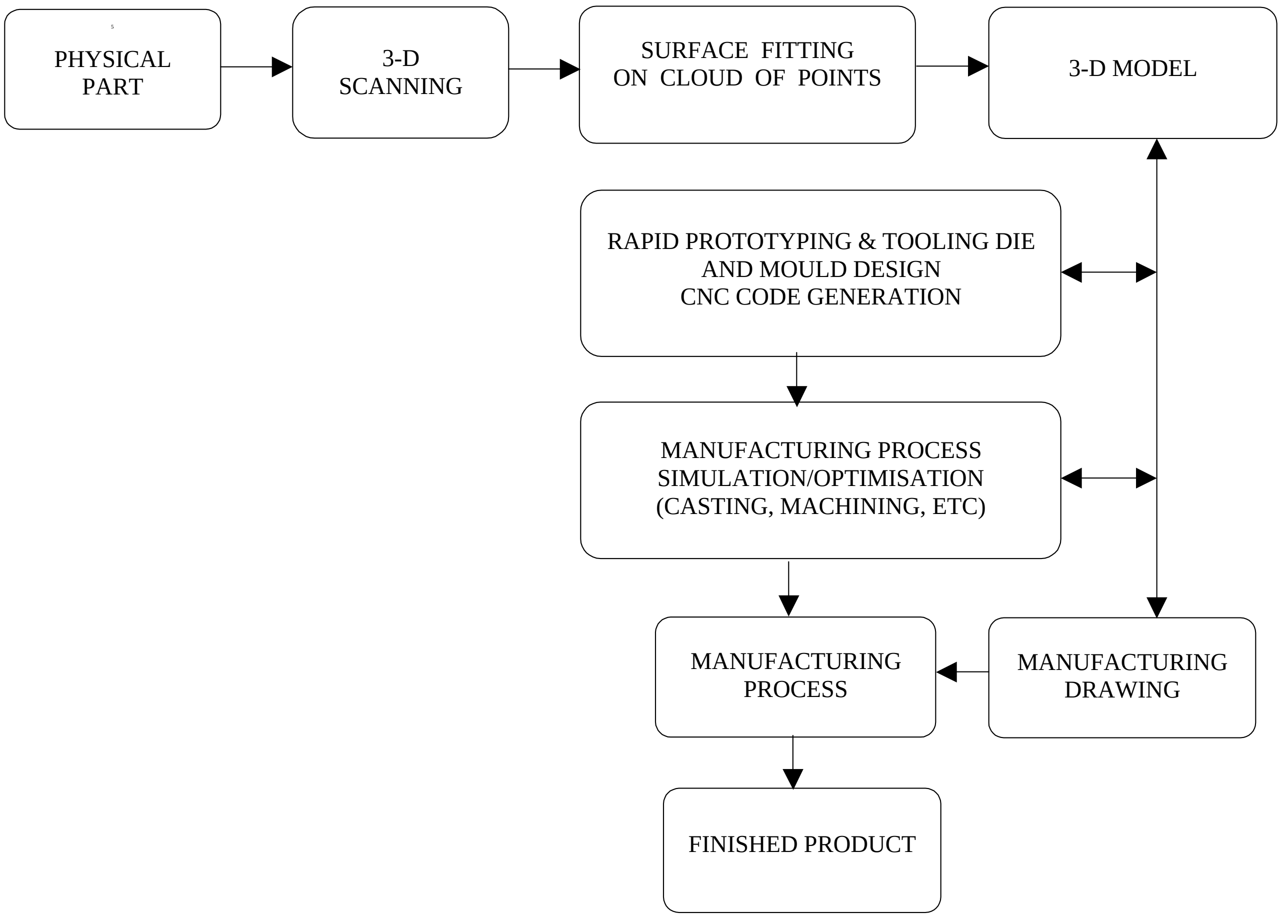


Figure 1. Computer-aided reverse engineering framework

model generation, material identification, and rapid manufacturing.

3. OBTAINING PART GEOMETRY

A 3-D model of the part is required for its rapid design, analysis, and manufacture. This can be created using a 3-D CAD system (such as AutoCAD, CATIA, I-DEAS, Pro-Engineer, SolidWorks, and Unigraphics). However, creating the solid model, especially parts with intricate geometry, is a cumbersome and time-consuming task.

An alternative approach involves automatic digitising of the surface of a physically existing object. Putambenkar[2], *et al*. describe the steps involved and the different techniques for CAD model generation. Essentially, there are two ways of digitising, contact type and non-contact type.

3.1 Contact Digitising Technique

In this method, there is physical contact between the measuring instrument and the surface being measured to record as many dimensions as possible. The simplest approach involves manual measurement of a model's dimensions. Hand tools such as micrometers, vernier calipers, and gages are used to capture the critical dimensions needed to generate a part drawing. A more sophisticated approach is to use a coordinate measuring machine.

3.2 Non-contact Digitising Technique

Non-contact digitising technique is that where the data acquisition device does not physically touch the part. There are two classes of non-contact technique: *Active* and *passive*. Active technique needs the use of structured lighting and reflection from the object, whereas passive technique works with the ambient light. There are various types of non-contact scanners such as laser scanner, computer-assisted tomography, Moiré interferometry, and white light triangulation.

3.2.1 *Laser Scanning*

It includes a probe that emits low-energy laser beams, a scanning mechanism that projects the laser beam onto the surface being digitised, and optic receptors with collecting lenses for detecting the reflected laser beam. A narrow beam of laser light is projected onto the surface of the object with a laser line of sight (LOS) angled approximately 30° to 45° wrt the receiving sensor LOS. The triangulation technique is used to determine the coordinate position of that point on the surface. This method generates one (x, y, z) data point per measurement.

3.2.2 *Computed-assisted Tomography*

It utilises an x-ray with multiple sensors to create a picture of a thin slice of an object along with the associated dimensional data, similar to medical CT scanning. The equipment repetitively scans the object, one cross-sectional slice at a time, and builds a dense point cloud in each plane. By measuring the amount of x-ray energy absorbed by the part, the shape of the part and its interior can be estimated. The distance between the slices is decided based on the details required. A 3-D CAD model can be generated by combining the 2-D slices using suitable software (such as Mimics from Materialise, Inc). The main advantage of this process is its ability to capture internal features, including anomalies. The entire geometry, regardless of complexity, can be obtained in one scan, eliminating the need for merging different point clouds.

3.2.3 *Moiré Interferometry*

It uses structured lighting. It is an optical technique based on interference fringes between the incident light and the reflected light. The shape and distribution of the fringes give information about the shape of the part. Typically, this method projects a fringe pattern of light (white bands and dark shadows) onto an object, which is then viewed through a similar reference pattern. The projected pattern, when viewed by an operator appears to pulse with the reference pattern creating a Moiré pattern. If the object is relatively flat, this Moiré pattern appears uniform in structure. If the object has surface variations, the Moiré pattern will have distortions that can be related to the shape of the object.

3.2.4 *White Light Triangulation*

It is a passive method using an optical technique based on stereovision. The underlying principle is similar to laser scanning. Measurement is based on the angle of the projected light, the angle of the reflection captured, and the positions of the source and the camera. In white light triangulation, the source emits white light. The main advantage of this process over laser scanning is that a grid of points are all scanned (triangulated) and measured in parallel. Various views of the object are statically captured. With large objects or objects with complex surfaces, several measurement views from varying angles are recorded. These views are transformed and merged to create one 3-D point cloud. This process is much faster and more accurate than laser scanning method because there is much less movement due to the static capture of each of the views.

The result of all digitising methods is point cloud data or cloud of points (COPs), which are random and unstructured collection of x, y, z coordinates. It is difficult to handle such huge point data sets directly in CAD software. Reverse engineering software such as Geomagics, Imageware Surfacer, Magics, Pro/Scan Tools, Rapidform and STRIM are specially developed for this purpose. Part features can be extracted by partitioning the 3-D data into non-intersecting homogenous regions; which is referred to as segmentation. After this, conventional CAD software is employed to fit various types of surfaces to segmented data[3].

4. MATERIAL IDENTIFICATION

Identifying the material composition of the existing part is the second most important task. There are several well-established nondestructive and destructive techniques to find the composition of part material.

Visual identification of the material can be made if exact chemical composition is not critical. A large majority of reverse engineering components may require destructive testing to determine material composition. It is critical that the engineer ensures that all physical and geometric features have been captured and identified prior to destructive testing. Some of the material identification techniques are:

4.1 Analytical Chemistry

In this procedure, successions of entropic solutions are subjected to various titration steps. These steps attempt to form specific precipitates that will define the chemical composition of the base material. This approach works well in non-organic chemistry. It does require destruction of the test sample, and is time-consuming and labour-intensive. The accuracy of this process is limited to parts per thousand range and requires some expertise for correct results.

4.2 Mass Spectrometry

Mass spectrometry or vapour-phase chemistry utilises spectrometry to determine the constituent atoms of a sample. The sample is heated until vaporisation begins. The resulting gaseous mixture is viewed through a spectrometer, which identifies the constituent elements by the spectral lines, or frequencies the gas absorbed. Current spectrometers are capable of detecting percentages of elements in parts-per-thousand to parts-per-million ranges. The major limitation of the spectrometer is that the exact chemical composition must be inferred from the atomic ratios. This process requires some expertise and experience, particularly in relation to organic compounds. The mass spectrometry approach is, however, relatively quick and will detect all the constituent elements of the sample.

4.3 Scanning Electron Microscopy Technique

The scanning electron microscope (SEM) uses energy dispersive x-ray (EDX) process. It is a very quick and accurate method, although it is limited to atoms with atomic weights greater than 11. The operator has to make the use of a known target sequence to calibrate the responses. This technique is capable of detecting chemical constituents in the parts-per-million range. Like other methods, this technique decomposes the sample into constituent atoms, leaving the chemical composition open for interpretation. This process has relatively poor resolution when analysing carbon, and none at all for hydrogen. Therefore, most organic substances cannot be analysed by this process. The EDX is most effective against a metallic compound, and provides a real-time measurement. Unless the laboratory routinely performs EDX measurements, the setup time for SEM may be relatively long and painstaking.

In many applications, it may not be necessary to use the original material for the reverse-engineered part. There are several benefits of material substitution in the reverse engineering process. The original material may no longer be available, or the previous material sources may have unreliable domestic or overseas suppliers. A new material may be more suitable for the product, resulting in better material characteristics and properties such as improved resistance to wear, stress, corrosion, fatigue, as well as easier maintenance and repair qualities. A new material may have a reduced raw material cost or processing cost through ease of manufacturing, leading to increased manufacturability of products. Recent environmental laws prohibit the use of certain materials in current manufacturing processes; therefore, a material substitution may sometimes be required.

5. RAPID MANUFACTURING

The rapid manufacturing techniques enable complex-shaped parts to be produced directly from a computer model without conventional part-specific tooling or machining. There are two routes for fabricating the part, the first one is the direct route in which the part is produced in plastic, resin or paper directly from the CAD data using a suitable rapid prototyping system, and the second is the indirect route in which the rapid prototyping parts can be used as masters for fabricating the tooling through a suitable rapid tooling method using epoxy, polyurethane or silicone rubber.

The parts produced by direct or indirect routes in resin, paper, plastic, or wax material can be used as a pattern or mould for sand casting or investment casting as appropriate. This enables producing near-net shape metal parts, which can be machined to final dimensions and tolerances. The CNC program required for the machining can also be generated directly from the CAD model of the part using CAM software.

5.1 Direct Routes

5.1.1 *Rapid Prototyping*

The rapid prototyping technology is an additive process based on the philosophy of fabricating the cross-sectional layers of paper, wax, or plastic on top of each other to create a physical part[4]. The sections are generated from a 3-D CAD model of the part and then fabricated using one of the several rapid prototyping techniques available. All techniques employ the same basic four-step process: (i) convert the CAD model to STL format, (ii) slice the STL file into cross-sectional layers about 0.01 mm to 0.7 mm thin, (iii) construct the layers of the model one atop another, and (iv) postprocessing such as cleaning and curing. Major issues involved in these steps are:

Step 1. *Conversion to STL format*

The various CAD packages use different schemes to represent solid objects, though the STL format has been adopted as the de facto standard of the rapid prototyping industry. The first step, therefore, is to convert the CAD file (which could include information about part features and analytical representation of part surfaces) into an STL file. The STL file represents a surface in terms of triangles, and stores each triangle in terms of vertex coordinates and the direction of the outward normal. It cannot represent curved surfaces exactly; increasing the number of triangles improves the accuracy at the cost of a bigger file size, which requires more time to preprocess and build. So, the designer must balance part accuracy with file size to produce an optimal STL file.

Step 2. *Slicing the STL file*

In the second step, preprocessing software supplied by the manufacturers of the rapid prototyping machines is used to process the STL file. It allows the user to adjust the size, location, and orientation of the model. Build orientation is important for several reasons. First, the generation of an auxiliary structure to support the model during fabrication. Supports are useful for delicate features such as overhangs, internal cavities, and thin-walled sections. Second, properties of rapid prototypes vary from one coordinate direction to another. For example, prototypes are usually weaker and less accurate in the z (vertical) direction than in the x-y directions. Third, the part orientation partially determines the time required to build the model. Placing the shortest dimension in the z-direction reduces the number of layers, thereby shortening the build time.

Step 3. *Part fabrication*

The third step is the layer-by-layer fabrication of the part. Using one of several techniques, the rapid prototyping machines build one layer at a time from the polymer, paper, or powdered metal. The machines are autonomous, requiring no human intervention during layer construction. There are four major rapid prototyping techniques, each with unique strengths. These are selective liquid solidification, semi-liquid deposition, sheet laminating, and powder binding[5].The stereolithography (SLA) developed by the 3-D Systems, Inc, uses photosensitive resins cured with an ultraviolet laser. The SLA QuickCast is a variation of the stereolithography process giving a hollow honeycomb structure of polymeric material. The fused-deposition modelling (FDM) system developed by the Stratasys Inc involves extrusion and fusion of the ABS-based polymer wire. In laminated object manufacturing (LOM) system developed by the Helysis Inc, a laser beam cuts sheets of paper, which are glued together into a solid part[6]. In selective laser sintering (SLS), a laser beam is used to selectively fuse-powdered materials such as nylon, elastomer, and metal into a solid object. In the thermojet printer from 3-D Systems, Inc, wax is deposited through multiple nozzles. Both the thermojet land SLA QuickCast patterns can be directly used for investment casting.

Step 4. *Postprocessing*

The fourth step is postprocessing. This involves removing the prototype from the machine and removing supports. Some photosensitive materials need to be fully cured before use. Prototypes may also require minor cleaning and surface treatment. Sanding, sealing, and/or painting the model will improve its appearance and durability.

5.2 Indirect Routes

5.2.1 *Rapid Tooling Operations*

The rapid tooling are the secondary operations, which produce a negative replica or mould from a master (produced by rapid prototyping or even conventional processes). Some of the indirect routes are useful for creating one-off parts; others are useful for small, medium, or large batch products[7]. The most widely used materials for producing rapid tooling include thermosetting polymers-epoxy resins, polyurethanes (elastomers and foams) and silicones. Metals, especially those with low melting point, are also used in some processes. The following are some of the important methods employed for rapid tooling:

- *Epoxy resin casting process* essentially involves mixing a suitable epoxy resin with a hardener and pouring it into a mould or onto the face of the master model placed in a box. A parting agent applied to the face of the mould facilitates easy release of the model from the mould.

- *Laminated shell moulding* involves creating a laminated shell around a master model using alternate layers of gel, epoxy resin, and glass cloth. While it is labour-intensive and time-consuming, it couples lightweight with good strength, suitable for large flat parts.

- *Polyurethane casting* involves pouring the resin around a master placed in a box, similar to epoxy casting. The material is more expensive than epoxy, but sets faster and can produce better output.

- *Silicone rubber moulding* involves pouring RTV silicone rubber around a master model and cutting open the mould after curing. These moulds have excellent chemical resistance, low shrinkage, and high dimensional stability, suitable for producing parts in polyester, epoxy, and polyurethane foam by injection moulding.

- *Metal arc spraying process* uses a high velocity electric arc metal spray generating system to deposit finely atomised particles of molten metal (usually kirksite) onto a master model surface to create a metal shell mould. The metal shell can be reinforced by epoxy.

- *Investment casting* requires an expendable master pattern (usually wax) that is coated with layers of silica slurry to obtain a shell, which is heated to remove the wax. Molten metal is poured in the shell and allowed to solidify to give a metal replica of the wax model.

6. CASE STUDY

A separator body [Fig. 2(a)] of a hydraulic oil filter assembly belonging to the special army vehicle was chosen to study the application of computer-aided technologies for rapid development of one-off intricate parts required for replacement purpose. The part neither had any drawings nor any other data related to its manufacturing. The investigation involved mainly three steps:

Step 1

Design data generation (part geometry by 3-D scanning, and material identification by spectrometry)

Step 2

Tooling fabrication (using rapid prototyping)

Step 3

Investment casting (after process planning and simulation).

The part model generated by reverse engineering was the connecting link between all the activities.

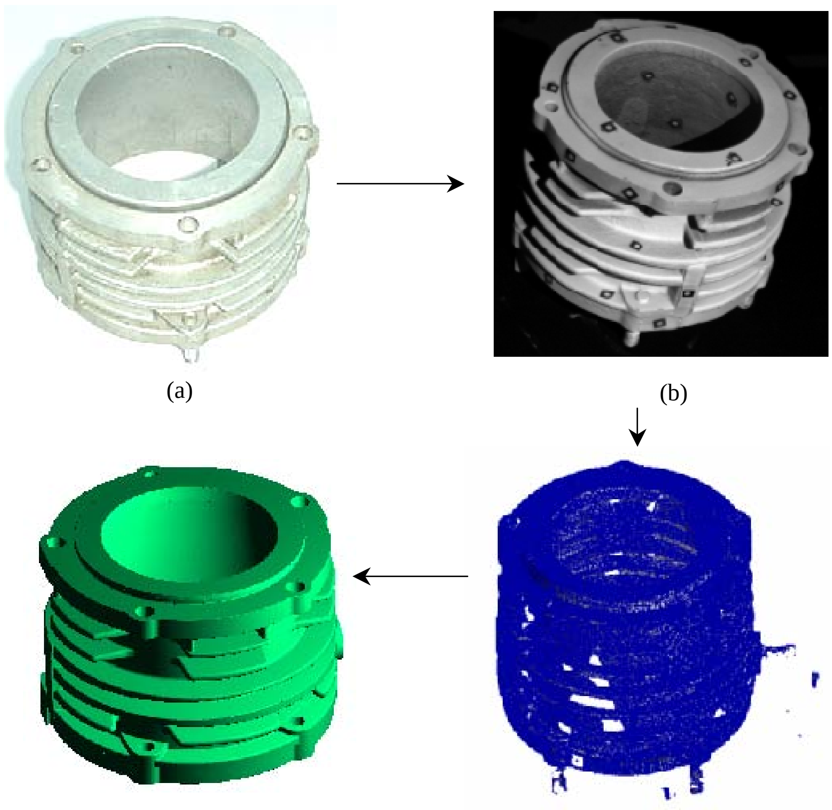


Figure 2. Reverse engineering of separator body: (a) original part, (b) original part with markers, (c) cloud of points, and (d) CAD model.

6.1 Part Geometry

For obtaining the geometry of the separator body part, an ATOS II optical digital scanner available at the Indian Institute of Technology, Kanpur, was used (Fig. 3). It uses Moiré interferometry principle. In this scanner, several images of the part were taken from different angles; markers were placed on the part for creating references for merging the images later. The images were automatically triangulated by the scanner software and bundled together producing a highly accurate reference file of the marker centres (X, Y & Z) for accurate scan patch placement in the global reference system. After scanning the part, the software polygonising module generated the point cloud based on a user-defined density or resolution. This data can then be exported in ASCII, STL, IGES or VDA formats.

For the separator body, 50 markers were used [Fig. 2(b)]. A total of 33 shots (pictures) were taken from different angles, taking about 4 h for scanning the entire part to obtain a cloud of points [Fig. 2(c)]. The 3-D CAD model [Fig. 2(d)] was automatically generated from the cloud of points by surface fitting using the Imageware Surfacer software. This involved fitting 1017 surface patches (consisting of 5967 curves and polylines) on the cloud point data. The surfaces were then stitched together to obtain a watertight CAD model of the part. An allowance of 3 mm on all machined surfaces and shrinkage allowance of 7 per cent (metal and wax included) were added to obtain the CAD model of the casting. The part model was used for fabricating a prototype, whereas the casting model was used for fabricating wax patterns for investment casting.

There were no hidden features in the separator body part on ATOS II optical digital scanner (Fig. 3). Otherwise, the sample part would have to be cut in a plane passing through the internal features to enable their scanning. This however, leads to destruction of the sample. External surfaces must therefore be scanned first before cutting the sample.

Figure 3. ATOS II optical digital scanner

6.2 Material Analysis

Direct-reading spectrometer was used to determine the composition of the material. The following material composition was obtained using spectroanalysis:

Aluminium	90.25 %
Copper	0.06 %
Iron	0.43 %
Magnesium	0.38 %
Manganese	0.22 %
Silica	8.66 %

Using IS: 617-1975, the following nearest standard of material: Grade 4450 was selected. It has the following composition:

Aluminium	90.60–91.85 %
Copper	0.10 %
Iron	0.50 %
Magnesium	0.20–0.45 %
Manganese	0.30 %
Nickle	0.10 %
Lead	0.01 %
Silica	6.50–7.50 %
Tin	0.05 %
Titanium	0.20 %
Zinc	0.10 %

The hardness measurement of the component was done using Rockwell hardness tester and was found to be 77.66 R_B (Rockwell B scale). Microstructure analysis was carried out using a ZEISS ICM405 microscope integrated with image capturing and processing software (MultiCam Easy Grab3.1, from Euresys) and Image Analyser software (Image Pro Plus4.5 from Media Cybernetics, Inc.).

An *aluminium-silica* alloy produces a very coarse microstructure, in which the eutectic comprises large plates and needles of silicon in a continuous aluminium matrix, as shown in the microstructure analysis in Fig. 4.

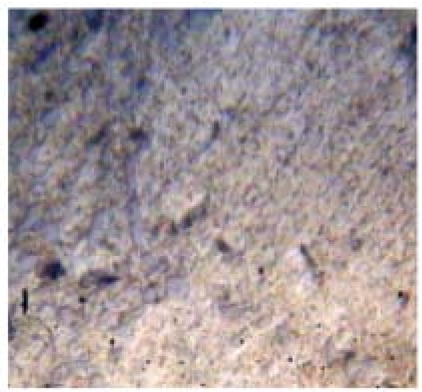


Figure 4. Microstructure analysis of aluminium-8.66 per cent silicon alloy shows large needles of silicon in aluminium matrix at 300X.

6.3 Process Planning

The 3-D CAD model of the casting part was used for designing and simulating the casting process, using AutoCAST software as shown in Fig. 5.

The main input is part model available as an STL file (ASCII or binary format) created by a solid modelling software; cast metal selected from a library that includes grey iron, ductile iron, steel, alloy steel, and alloys of aluminium, magnesium, copper, and zinc; and process which includes sand, shell, and permanent mould (gravity die). Based on these input, the software suggests casting orientation,

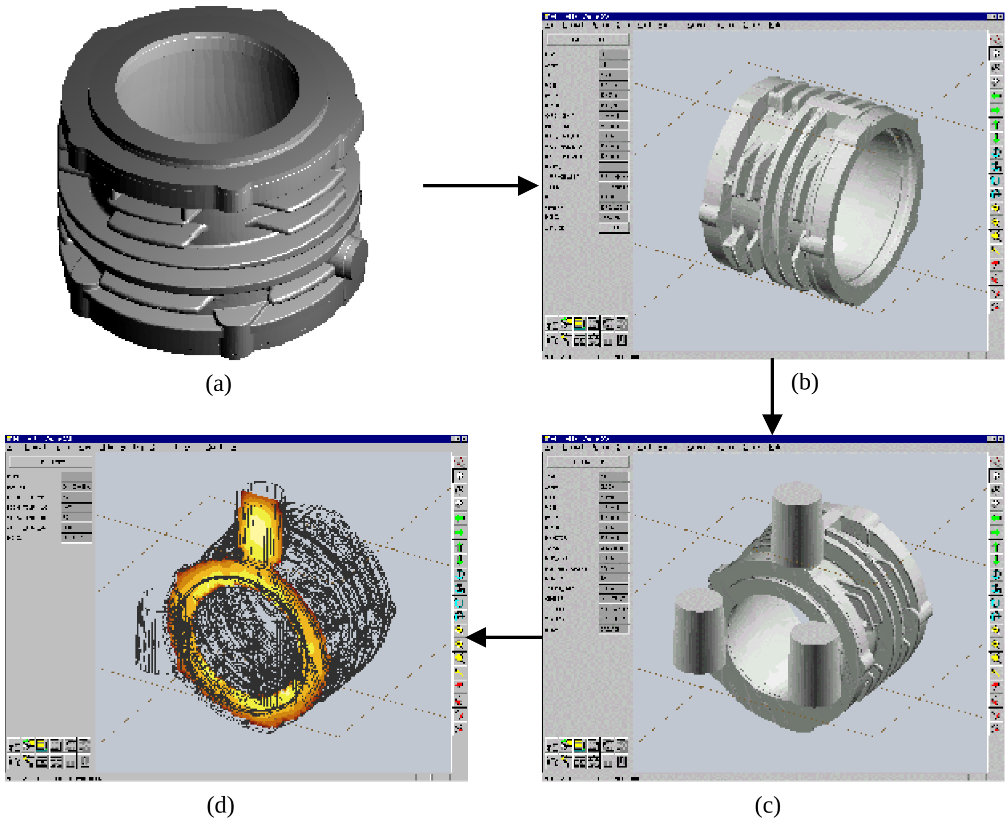


Figure 5. Casting and analysis: (a) casting model, (b) model imported and oriented in AutoCAST, (c) three feeders created, and (d) identification of hot spots.

parting position, feeder location and size, and gating design. The user can override these suggestions. The solid models of casting elements (feeder, gating, etc) are automatically created based on the design. Then, the process is simulated to predict internal defects (such as shrinkage porosity and inclusions). The user can modify the casting design and simulate the process until internal defects are minimised and yield is maximised. The summary of solidification analysis of the separator body is as follows:

(a) Preliminary analysis (without a feeder) showed a circular zone of shrinkage porosity in the left side of the casting [Fig. 5(b)].

(b) Two-side feeders (height: 50 mm, diameter: 34 mm (top), 38 mm (bottom), neck:12 mm x 24 mm) were modelled and attached to casting. Solidification analysis was performed and different casting sections were checked. A hot spot region at the top was still visible.

(c) A top feeder (height: 50 mm, diameter: 34 mm (top), 38 mm (bottom), neck: 30 mm x 14 mm) was modelled and attached. The results were comprehensive, but the neck size can be further increased depending on the results of the first trial.

6.4 Prototype Part & Casting Pattern

The stereolithography (SLA) rapid prototyping process was used for fabricating the prototype [Fig. 6(a)] of the part in photo-curable resin material on an SLA5000 machine. Layer thickness was set to 0.1 mm. The fabrication took 22 h. This was followed by clearing the supports using acetone, drying in an air stream, and treating with ultraviolet light for 2 h for improving the strength.

Two investment casting patterns were made using SLA QuickCast [Fig. 6 (b)] and thermojet rapid prototyping [Fig. 6 (c)] processes. A layer thickness of 0.1 mm was used in both the processes.

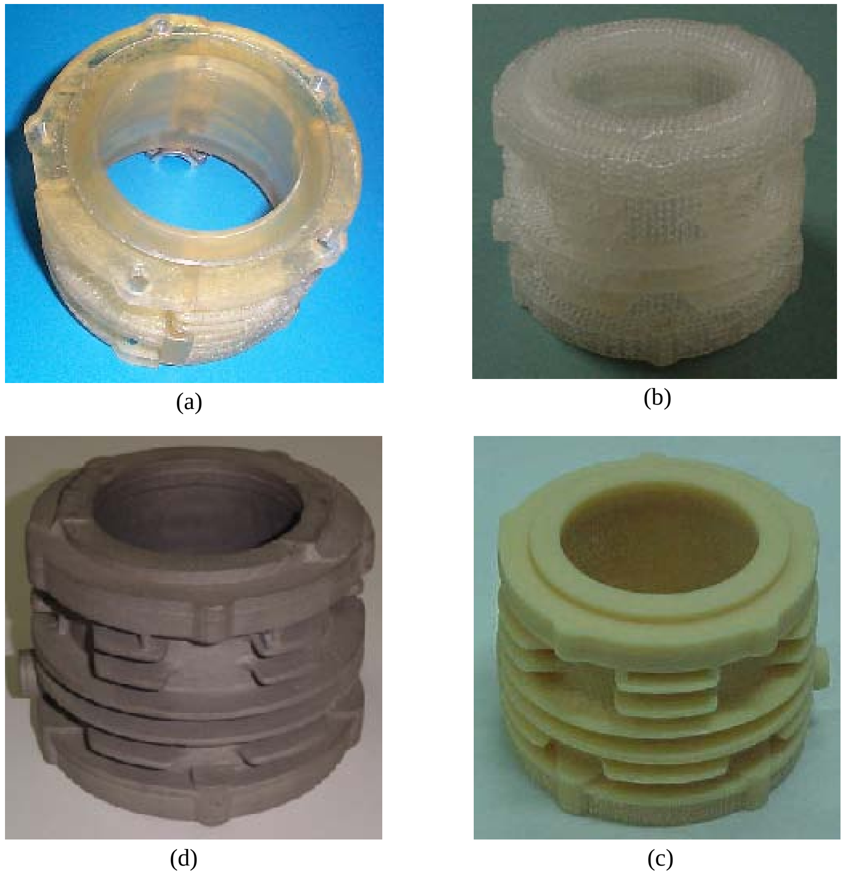


Figure 6. Rapid tooling and investment casting: (a) SLA part, (b) SLA QuickCast part, (c) thermojet part, and (d) investment cast part.

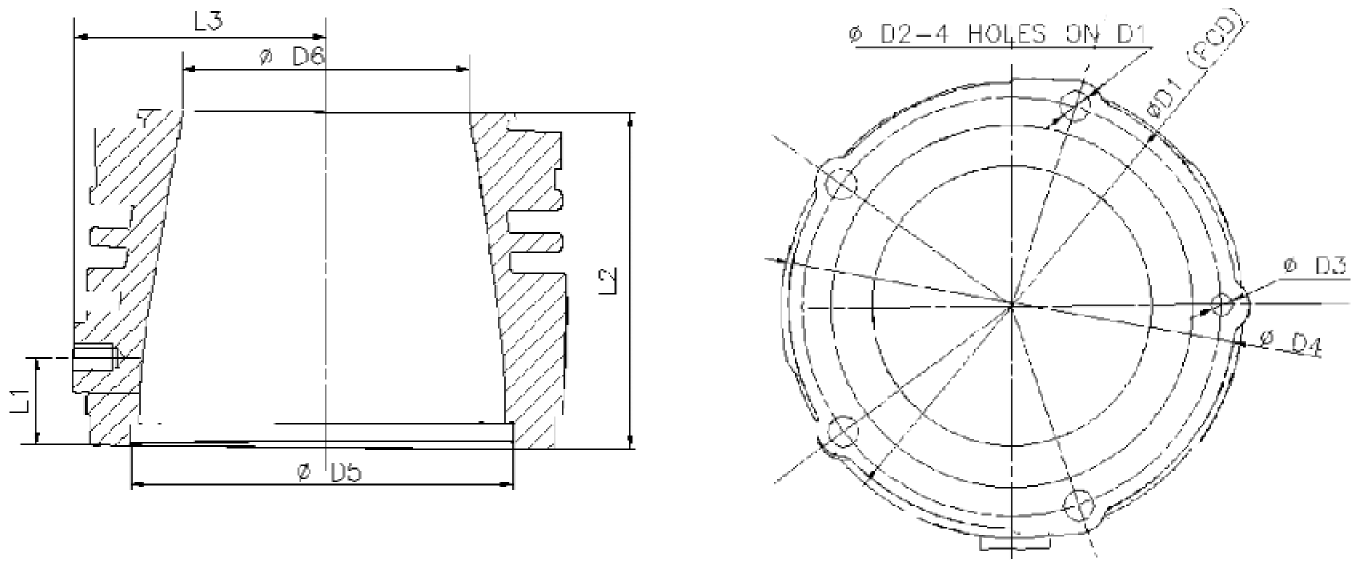
The fabrication took less than 12 h for each pattern. The QuickCast process is a variation of the stereolithography process giving a hollow honeycomb structure of photo-curable resin material. The thermojet material was closer to the wax used in investment casting process and was also more economical than QuickCast patterns. It was therefore chosen to fabricate the separator body by investment casting process [Fig. 6 (d)].

6.5 Dimensional Comparison

Dimensional errors may be introduced during 3-D scanning, point-data processing, solid modelling, and rapid prototyping. Figure 7 shows the key dimensions measured for the original part, 3-D CAD model, and SLA prototype. The results have been presented in Table 1. This includes the deviation of CAD model and SLA prototype wrt the original part, as well as the deviation of the SLA prototype from the CAD model.

7. RESULTS & DISCUSSION

The CAD model obtained via reverse engineering consists of a large number of surface patches stitched together on the cloud data. It is very tedious to make a water-tight volume model, due to unavoidable discontinuities among the stitched surfaces. Secondly, handling of reverse engineering CAD model is cumbersome owing to its large size. Some reverse engineering software provide facilities for surface evaluation and model inspection by measuring the difference between surface model and cloud data, and surface-curve discontinuity and surface-to-surface discontinuity. They also enable automatic gap filling and repairing. In general, the quality of 3-D CAD models created using a conventional solid modelling software is better than that obtained through reverse engineering. Reverse engineering is suitable when no drawings are available and the part has an intricate geometry.



SECTIONAL VIEW

TOP VIEW

Figure 7. Notations of dimensions used for dimensional comparison

The separator body is a medium-complexity part, owing to the fins, taper on the central portion and curved geometry. Solid modelling using conventional CAD software would have taken at least a working week. In contrast, it took only four hours for 3-D scanning and 8 h for surface fitting (Table 2).

While metal casting is the most economical route to manufacture an intricate part and for pattern development, and casting trials are the major bottlenecks, consuming significant resources and taking over 60 per cent of the total time. Manufacture of a wooden pattern for the separator body would have taken at least 3 weeks, and subsequently at least 3-4 shop floor trials over 2-3 weeks would have been required to get the desired quality. In contrast, the rapid prototyping wax patterns were made in less than 12 h and the casting process was optimised in just 4 h.

8. CONCLUSION

There is an increasing interest in reverse engineering of parts whose drawings (geometric, material, and manufacturing details) are not available,

Table 1. Dimensional comparison

Dimension	Original part (O) (mm)	CAD part (C) (mm)	SLA RP part (R) (mm)	Original and CAD part (C–O) x 100 (% error)	Original and RP part (R–O) x 100 (% error)	CAD and RP part (C–R) x 100 (% error)
Dia D1	124.00	123.71	122.98	-0.23	-0.82	-0.59
Dia D2	9.00	8.98	8.61	-0.22	-4.33	-4.12
Dia D3	6.00	6.12	5.98	2.00	-0.23	-2.18
Dia D4	132.00	133.34	132.45	1.01	0.34	-0.66
Dia D5	108.00	108.98	109.08	0.90	1.00	0.09
Dia D6	84.00	83.00	82.02	-1.19	-2.36	-1.18
Length L1	25.00	25.02	25.52	0.08	2.08	1.99
Length L2	95.00	95.76	96.61	0.80	1.69	0.88
Length L3	71.00	71.86	71.96	1.21	1.35	0.14

Table 2. Details of time taken for various processes

Process	Time taken (h)
3-D scanning of part	4
Surface fitting	8
Rapid prototyping wax pattern	12
Casting simulation	4
Investment casting	80
Machining	12
Total	120

especially those required one-off or in a few numbers such as for replacement of broken and worn out parts. It is facilitated by the technologies such as non-contact scanning, rapid-tool manufacturing (using rapid prototyping and rapid tooling methods) and process parameter optimisation through simulation. This investigation focusses on integrating these technologies to achieve a significant reduction in manufacturing time and associated costs for one-off products compared to that achieved through the conventional routes. This has been demonstrated by rapid development of a separator body of a hydraulic filter assembly belonging to the special army vehicle, which had no drawings or any other data related to its manufacturing. An exhaustive benchmarking exercise of all possible routes for rapid manufacturing was beyond the scope of this current investigation and is a subject of further study. It is hoped that this study will motivate the Defence R&D establishments to explore and adopt computer-aided reverse engineering for indigenous development and further refinement of even complex parts.

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