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ORIGINAL ARTICLE

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Rapid and cost-effective manufacturing of high-integrity aerospace components

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Abstract This paper presents a comprehensive set of theoretical investigations and industrial applications of computer-based rapid manufacturing technology for high-integrity aerospace components. Two rapid manufacturing processes have been proposed by integrating rapid prototyping, high-speed machining (HSM), reverse engineering and geometric computation theory. They have been validated through trial manufacturing of a matrix of current aerospace components embracing critical design features to be found across the aerospace industry. Applied to future development programmes, this research will provide aerospace companies the benefits of significant decrease in product introduction lead-time, savings in non-recurring product introduction costs and considerable reduction in manufacturing costs for "one off" and low volume service parts. The findings can also be applied to rapid prototype development in other industries, such as automotive and military.

Keywords Aerospace · High-speed machining · Rapid manufacturing · Rapid prototype · Reverse engineering

1 Introduction

With the establishment of World Trade Organization and availability of web-based technology and agile manufacturing technology, customers are expecting the latest products with first class services at a reasonable cost. Manufactures have to take their customers needs into account to a higher degree than ever before, and design products in more dynamic ways to face the challenge of total customer satisfaction. Customers are "dictators" of product design and development. That is especially true for aerospace industry, and it is the trend in automotive industry as well. Customer-tail product design and development is different from the idea of mass customisation of products.

A product can be defined as a solution to a customer's problem or need and comprises of functional, psychological and service components, where the costs alone might not be sufficient to satisfy the different expectations of customers. In the existing world market, customers demand innovative, flexible and personal design in quality, performance, services and in the styling of the products. This is the idea of class customisation. In addition to these requirements, customers are also seeking the most reasonable purchase price to meet their needs.

It has been widely accepted that manufacturers have to change their fundamental product design and development philosophy to win shares of worldwide markets. This is especially true for high tech industries like aerospace and automotive. Product profit cycles are shrinking. In order to stay competitive, manufacturers should be able to attain and sustain themselves as "world class manufacturers". It means that manufacturers should be capable in delivering products in fulfilling the total satisfaction of customers; more specifically, this means higher quality products, the right time to market and reasonable costs.

This paper presents a comprehensive set of theoretical investigations and industrial applications of computer-based rapid design and manufacturing technology for high-integrity aerospace components. In the aerospace and automotive industries, a common product development task is to provide products to the world markets in the most competitive way. This requires that new products be designed and manufactured at a high quality, in short time and at low cost. Common product development process is market surveying (demanding), conceptual design, detail design, manufacturing and marketing [1]. Unfortunately, this process has been often seriously delayed because of the tremen-

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dous difficulties in the design and manufacturing of high integrity components.

Aerospace equipment manufacturers require the capability to produce high-integrity components in low volumes. The industry is driven by the need for complex products to meet enhanced technical specifications, but with reduced development costs, short production time and lower purchase prices. It has been widely accepted that in order to survive, the aerospace industry has to compete in world markets. For example, the IMI research framework identified that for UK manufacturers to be internationally competitive, there was a need to achieve:

- 30% reduction in manufacturing costs;
- 35% decrease in manufacturing lead-time;
- 40% compression in time to market; and
- 25% reduction in product introduction costs.

Securing these performance improvements remains fundamental to retaining and winning new business in the competitive global aerospace markets. The Foresight Steering Group had identified the need for an improved technology exploitation process for communicating with machines, design and systems integration and materials processing technology, as they are the basic requirements in achieving the performance criteria demanded by the global aerospace industry. The Rapid Manufacture of High Integrity Aerospace Components project (RAMAC) was funded to demonstrate the competitive benefits of integrating emerging computer-based technologies and to provide UK aerospace companies with the technology needed for the development and subsequent low volume manufacture of complex components. This paper presents the achievements in RAMAC.

There have been publications on rapid design and manufacturing [2–5], but, as far as authors are aware, there have not been any publications on comprehensive investigation and evaluation of various rapid manufacturing methods, such as rapid prototyping (RP), rapid tooling (RT), high-speed machining (HSM) and reverse engineering (RE), etc. This paper address these topics.

2 Rapid manufacturing technologies

Rapid prototyping and manufacturing technologies are new techniques to produce one or more pieces of a solid part from CAD data quickly, irrespective of the complexity of the shape. There are several different kinds of them: RP, RT, HSM, laser manufacturing (LM) and RV, etc. Though they can be used as an independent method, they are often integrated into a process for rapid manufacturing of high-integrity components. This section will briefly discuss the above technologies – their definition, development and application.

2.1 Rapid prototyping

Rapid prototyping (RP) techniques are methods that allow for the quick production of physical prototypes with the important benefit of reducing the time to market. In the past 14 years, a number of new RP manufacturing systems have been developed. These permit the conversion of the concepts of a complex component into a solid replica in a matter of days, where conventional prototyping systems would require weeks or months. This is manufacturing technology that allows “art to part” in a few days and has developed principally in the USA; it is now in use throughout the UK. New developments arrive continually. RP has now been accepted as a standard process in industries [6].

All RP techniques start with a computer generated software model of the part to be made. The computer then slices the part into thin layers and feeds information on the shape and dimensions of each layer to the manufacturing system.

The systems differ in the way the component is built up layer by layer. Nowadays, more than 30 different processes (not all commercialised) exist, and offer a high degree of accuracy and a large choice of materials. These processes are classified in different ways: by materials used, by energy used, by lighting of photopolymers, or by typical application range. The most successfully developed techniques are:

- Stereolithography, where the computerised information on the shape to be made guides a laser beam over a photosensitive bath of liquid resin. The resin is solidified under the beam of the laser and the component is built up layer by layer.
- Selective laser sintering, where the starting material is a bed of powdered wax, metal, or plastic and the laser fuses the laminated powder into the solid component.
- Laminated object modelling, where a laser is used to cut out shapes in an adhesive paper and successive layers are glued together.
- Fused deposition modelling, where the plastic material is extruded from a nozzle.
- 3D printing, where successive layers are put down by a printing technique.
- Sanders materials, where thermoplastic, wax and other materials are dispensed from the moveable print heads as a hot liquid that solidifies upon impact with the cooler build layer.
- And ballistic particle manufacturing (BPM), where a target is bombarded with direct streams of material (waxes, plastics, photocurable polymers, ceramics, or metals), building three-dimensional objects in much the same manner as an ink jet printer produces two-dimensional images.

One of the key areas that RP has developed is investment casting. This has been the result of the fact that most RP methods are capable of producing models that can be used as lost patterns for investment casting. However, the level of success can vary significantly between different RP methods. There has been some research done to develop and compare the use of RP models as lost patterns for investment casting [7–12]. Although these studies have led to some important developments in this field, the results have become irrelevant due to evolution of both the RP equipment and materials. The lack of up-to-date information creates a void in the industrial knowledge base, and has resulted in companies having difficulties in selecting appropriate RP technologies.

2.2 Rapid tooling

Rapid tooling (RT) is the result of combining RP techniques with conventional tooling practices to produce parts of a functional nature from electronic CAD data in less time and at a lower cost relative to traditional machining methods.

Only when the production quantity is massive can the expensive tooling cost be well justified. As a result, the means of producing tools quickly and more economically is especially important in small- batch manufacturing. Furthermore, in the product development cycle, there is always in need of some intermediate tooling to produce a small quantity of prototypes or working samples for marketing, functional testing, or production process design and evaluation purposes. In this respect, RT becomes more and more important to today's manufacturing industry.

Advantages of rapid tooling for manufacturing can be summarized as: 1) shortened tooling lead time, 2) low cost, 3) allows for functional testing of parts in early stages of design, and 4) the direct transfer of CAD data.

2.3 High-speed machining

High-speed machining (HSM) means different things to different machine tool vendors. It is widely accepted that the definition the HSM process means the use spindles with greater than 8000 rpm and cutting parts with much higher feed rates than normal Computer Numerical Control (CNC) machining. HSM is relatively new to the industry. In spite of little process knowledge and experience with the appropriate cutting tool technology, companies are still moving rapidly toward HSM. Approximately 30 percent of the companies in the U.S. and Japan are already using HSM, with the number even greater in Germany at 40 percent. The remaining companies in all these countries are considering making an investment in HSM or are interested in this new technology.

There have been some publications on HSM [15–18]. It provides an attractive alternative to the traditional CNC machining Electrical Discharge Machining (EDM) process. For example, it can dramatically reduce the mould lead-time. HSM reduces lead time requirements in both the machining and polishing phases of the process. Dramatic improvements can be accomplished because HSM machines operate at speeds five to ten times faster than traditional machine tools. They can directly machine the hardened tool steel as well as reduce or even eliminate the need to produce electrodes. The time-consuming grinding and polishing of moulds can also be greatly diminished since a high-quality finish can be produced by using a small step-over.

The HSM process can be further enhanced through the use of new spline-based tool paths called non-uniform rational B-splines (NURBS).

The use of HSM strategies normally requires that the material to be removed with very shallow cuts and with a small step-over. The goal of the cutting strategy is to have a constant chip removal volume with the cutter in constant contact with the material. The cut patterns that are frequently used for roughing are Z-Level cutting patterns with helical engages. In some cases, this approach is also used for finishing. Ideally, finishing passes on floors should be done with a follow contour method (inside-out or outside-in), and walls should be done with Z-Level profiling cutting, using a climb milling cutting convention. Due to the speed of the tool, gentle ramping engages are required, and plunging into the part must be avoided. In addition, cut patterns with sharp corners and quick turns should be minimized.

Several of the new HSM machine tools have controllers with look-ahead features (up to 180 blocks) to determine change in direction and will decelerate or accelerate the spindle as necessary. In addition, to achieve an optimal finish on the part, the step-over for the part surface should be equivalent to the feed per tooth on the cutter. This will result in small square surface patches.

The depth of cut is another important factor in HSM. The depth of cut should be less than 1/10 the diameter of the cutter for finishing. The result is very shallow cuts, which leads to the use of Z-level type cut patterns.

This method also can be used for the roughing and finishing of moulds. Tools for HSM applications normally require a special coating to extend their tool life. Another important factor is the use of balanced cutters. At high speeds, the use of a special coating will extend tool life and improve surface quality.

2.4 Reverse engineering

Reverse engineering(RE) is a method for constructing CAD models of physical parts by digitising an existing part. A typical RE system consists of two main parts: a measuring machine to digitise the physical model surface in the form of point cloud, and software to create the surface and solid models from the point cloud. A measuring machine is fitted with a digitising device that can be classified as contact and non-contact. A contact device is a probe and non-contact device is either a laser point/line scanner or a 3D-camera [19, 20].

RE is not only very good method for constructing CAD models of physical parts, but is also a powerful tool in inspecting various physical models, especially with complex spatial positions and orientation geometrical features.

2.5 Laser manufacturing

Laser manufacturing technology can be defined as methods for producing components by applying powerful laser energy in an organized way. There are many industrial applications of laser manufacturing technology. Most significant are: (1) laser cutting (carbon/alloy steels, aluminium, titanium, stainless steels and non-metals such as plastics, quartz, ceramics, rubber, wood and composite materials); (2) laser welding; (3) laser engraving; (4) laser cladding; (5) laser heat treatment; and (6) laser tube cutting (round, square or rectangular tubing).

Laser technology offers a number of advantages over more traditional machining methods:

- Laser welding requires no filler material and produces maximum penetration with minimum distortion.

- Laser tube cutting can produce complex geometries on round, square or rectangular tubing using an integrated rotary axis feature.
- And laser technology can be used to trim stampings and to perform intricate engraving, among other uses.

Due to the working principle of laser manufacturing, it is mainly used for sheet-metal work for cutting manufacturing. It is not a competitive and cost-effective method for the manufacture of components with complex features, such as those frequently found in the aerospace and automotive industries.

3 Cost-effective and rapid manufacturing processes for high-integrity components

As discussed above, rapid manufacturing technology is consists of methods for the rapid production of a product's physical components, and for fast quality evaluation – especially metrological inspection. Laser manufacturing is a very powerful tool for sheet metal cutting and process; RP, RT and HSM can be used to produce components with complex and irregular shapes; and RE is an innovative technology that is a much more efficient way to do metrological inspections than normal CMM or manual processes. In this paper, RP, RT, HSM and RE will be investigated and integrated into different processes for the efficient and rapid manufacturing of high-integrity components.

Two main rapid manufacturing processes have been applied: 1) process based on RP and RT and 2) HSM process.

3.1 Process 1 – based on RP and RT

This process investigates the two fundamental approaches to the rapid manufacture of castings: the direct casting of a sacrificial pattern and rapid tooling. The main purposes of this study is to establish the relative technical merits for each of the RE pattern and wax-tooling systems based upon the requirements for manufacturing Class A aerospace castings of varying size and complexity. Furthermore, it is also designed to examine the use of direct laser sand sintering technology to produce moulds for the manufacture of magnesium alloy and aluminium based castings. Magnesium is being used extensively for aerospace castings and it was important to establish a viable method for manufacturing rapid prototypes. The main procedure of this process is as follows:

- Manufacturing of wax models using RP
- Metrology inspection of RP models using RE technology
- Component casting
- Quality evaluation of castings.

Figure 1 illustrates the steps of this process.

3.2 Process 2 – based on HSM

High-speed milling technology is undertaken using the same two components that have been identified for evaluating RE systems, to investigate an alternative way for the rapid manufacturing of components with complex geometrical features. The main procedure of this process (Fig. 2) is as follows:

- Machining strategy determination
- Part programming and NC code verification
- Simulation and optimization of the machining process
- Machining of components
- Metrology inspection using RE
- Quality evaluation.

4 Case studies

This section illustrates the proposed processes for the rapid manufacturing of several high-integrity aerospace components.

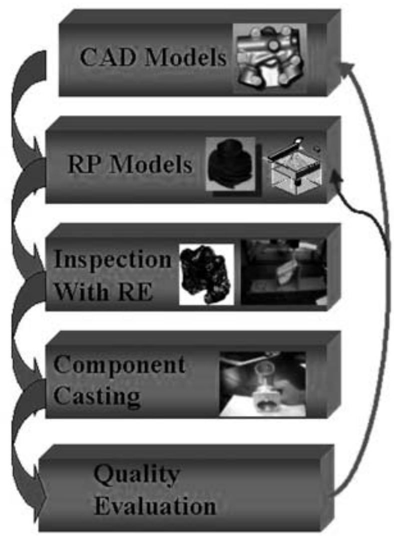


Fig. 1. Process based upon RP, RT and RE

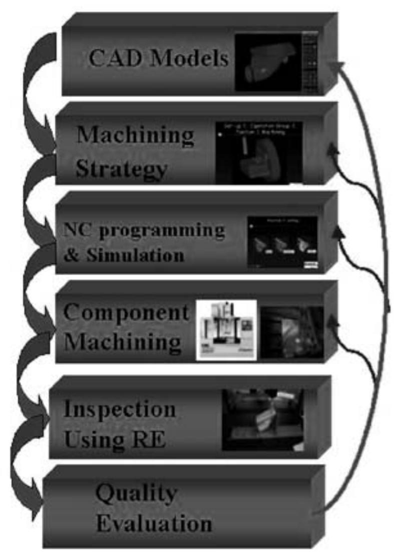


Fig. 2. The process based upon HSM and RE

Table 1. Aerospace component matrix

	Process 1 Investment cast	Sand cast	Process 2 High-speed machining
Small thin wall	TA, GA	–	TA, TB
Small thick wall	BA	GB	BA
Large thin wall	BB		
Large thick wall	GB	TC	TC

The initial work was to collaborate with industrial partners to define a matrix of current aerospace components (see Table 1). The components are a TRW inducer (TA), impeller (TB) and MPDV fuel metering unit (TC); a BAE Systems' pipe elbow (BA) and AFT shelf fairing (BB); and, a GKN Westland helicopter's oil jet (GA) and accessory gear box (GB). This matrix of components embraces the critical design features common across many aerospace components. Each item selected was of direct interest to a partner company who could provide current information on test methods, manufacturing routes, and production costs. These components were used to investigate the proposal processes and make comparisons between them.

4.1 RP, RT and RE

RP and RT technology was undertaken using two components, the GKN Westland helicopter oiljet (Fig. 3), and the BAE Systems pipe elbow (Fig. 4). It was expected to obtain the information necessary for a direct comparison between alternative manufacturing routes.

4.1.1 Investment of oil jet

A) Component description. As described in Sect. 2, there are a number of different RP technologies. They can be used to create various RP models. To provide the industrial users with a practical means of quality evaluation, it is required to manufacture the same component with different technologies. To limit the cost and time to manufacture the RP models and produce the final castings, a small, relatively simple part with difficult-to-measure geometrical features was selected for these trials. This component, the GKN Westland oil jet, is shown in Fig. 3. Eight geometrical parameters of these patterns are required to examine the metrological properties before casting, as shown in Fig. 3.

Fig. 4. The TRW inducer

Frame xc_1y is the part co-ordinate system with origin at c_1, and x-axis is parallel with one of the edges of the base. This is the reference frame for scanning. Among them, four are orientation angles ($\alpha_1, \alpha_2, \alpha_3$ and β), two are diameters (d_1 and d_2), one is roundness (R_d), and one is surface flatness (T). The four orientation angles are used to define the spatial orientation of the jet pipe. β is the angle between the jet pipe axis and its projection on the support base of the part. If this projection line is used as axis y', then the perpendicular line is axis x'. Frame $x'0y'$ can be defined by locating its origin at the centre of a circle determined by the centres of three holes on the support base. The centres of these three circles are denoted by c_1, c_2 and c_3. α_2 is the angle between the opposite direction of axis x' and the line $0c_2$, which joins the origin of frame $x'0y'$ and the centre of hole one. α_1 and α_3 are the angles between the opposite direction of line $0c_2$ and lines $0c_1$ and $0c_3$, respectively. The nominal values of these three angles are $\alpha_1 = 45°$, $\alpha_2 = 37°$ and $\alpha_3 = 45°$, respectively.

B) RE models. To achieve an objective evaluation of various RP models, six RP systems were used in these trials, as listed in Table 2, and the eight different models were constructed using the building conditions are listed in Table 3. Six samples of each model have been produced. Therefore, the total number of RP models is 48.

C) Quality evaluation of RP models. The quality of a RP model is reflected by various factors, including preciseness (0.00. . . . mm), surface finish (topography), cost corridor (specific for the number of parts produced), preparation time, suitability for geometry (simple, filigree, complex, thin-walled, etc.), application (compatibility for the standard casting process and casting

Fig. 3. The GKN Westland oil jet and eight parameters

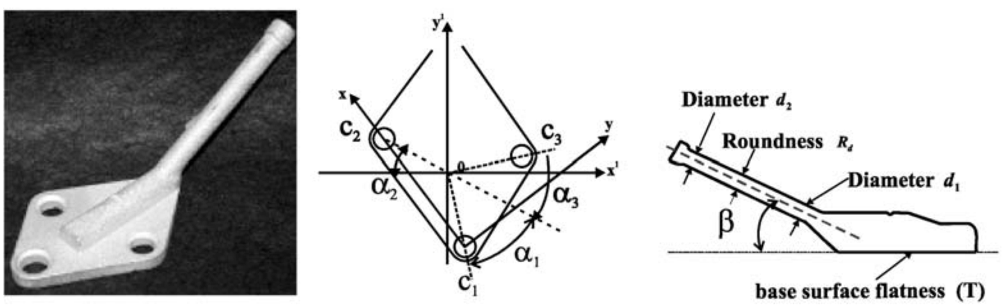


Table 2. List of RP systems used in trial

RP technology	Machine	Material & Model form
Stereolithography	SLA5000	SL5195 quickcast II
Selective laser sintering	DTM sinterstation 2500	DTM castform, DTM trueform
Laser sintering	EOSint P350	EOS polystyrol
3D systems MJM	Actua 2100 thermojet	Thermojet 75, thermojet 88
Sanders 3D plotting	Model maker II	ProtoBuild
Stratasys FDM	FDM1650	ABS P400

Table 3. Build details for the RP models

MODEL TYPE	Build time for six models (h)	Layer thickness (mm)	Models manufacturer
EOS polystyrol	8.6[e]	0.15	EOS
DTM trueform	5.5[e]	0.1	Rover Group
DTM castform	5.5[e]	0.10	DTM
Sanders	50	0.05	Alpha Mech. Engineering
Actua	6.5[e]	0.05	Rover Group
Thermojet	Not know (4–5[e])	0.05	3D systems
FDM	15 (solid build)	0.25	Laser Lines Ltd.
SLA quickcast	3	0.15	Rover Group

[e] estimated time

quality, etc.), and practical features (cleaning, finishing, etc.). Some of them are technical issues, such as preciseness, surface finish, suitability for geometry, and application, while the others are related with economic considerations. This paper will focus on the technical issues. The following work has been carried out to evaluate the quality of various RP models:

- Preciseness
- Surface finish
- Visual inspection of RP patterns and final casting
- Compatibility with the standard casting processes
- Casting quality based on X-ray analysis

Among the above five components, it is most difficult to reliably measure eight geometrical parameters to examine the preciseness of RP models. From Fig. 3, it can be seen that it would be very difficult, imprecise, and time consuming to find the geometrical parameters $\alpha_1, \alpha_2, \alpha_3$ and β, if traditional metrology methods and normal CMM machines are employed to carry out the metrology inspection of the oil jet. For this reason, a RE approach is used.

The geometrical accuracy has been examined by scanning RP models to generate point clouds which were processed using RE software surfacer. It has been found that the sander models showed the best combination of accuracy and repeatability, followed by the DTM castform and trueform, which virtually tied for second place. The actua and SLA models gave similarly promising scores. The FDM and EOS polystyrol models were unsatisfactory. Thermojet models gave very poor results – likely due to the thermally induced stress resulting from the machine's very high build rate. This factor of speed versus accuracy must be considered when using the machine.

Each of the model types was examined and visually assessed on the basis of surface finish, feature definition and quality of holes in the base. It has been observed that: (a) of the different systems, the sanders models gave the best combination of surface finish, feature definition and quality of three holes; (b) the stereolithography, actua and thermojet models gave excellent surface quality and reproduction of features but were marred by the presence of supports on the underside of the models. This problem could have been reduced by additional clean-up operations; (c) in the case of the actua and thermojet models, recent improvements in support removal techniques include the use of hot water to soften supports prior to removal and the use of paraffin to manually polish the underside of models, have been introduced. However, there were concerns that these additional processes would undermine the accuracy of the parts and for this reason it was decided to employ the minimum amount of manual post processing on the models; (d) although the quality of the FDM models was generally very good, with no effect from the supports, there was a pattern on the surface of the models produced by the extruded tracks; (e) of the laser sintered samples the DTM trueform models had the best surface finish, feature definition and hole quality; (f) trueform has been superseded by castform for the manufacture of investment casting patterns. Unfortunately, despite good quality, the castform models lacked the sharp feature definition of the trueform models; and (g) the EOS polystyrol models were rather disappointing, having a granular, gritty surface with very poor feature definition.

D) Investment casting. In order to retain models from each RP system for future analysis, only three samples from each system were processed into castings. Where possible the standard investment casting procedure was used, as described below:

1. **Assembly** – Three samples from each modelling system were assembled together on a single wax runner bar attached to a standard wax cup.
2. **Shelling** – The assemblies were given six coats of ceramic and dried using the standard production method.

3. **Autoclave** – The ceramic moulds were de-waxed using 7 bar steam pressure for a duration of 12 min.
4. **Firing** – Ceramic moulds were fired at a temperature between 750–900 °C for a period of 15–45 min.
5. **Shakeout** – Ceramic moulds were inverted and shaken to remove any ash or ceramic debris.
6. **Casting** – Ceramic moulds were preheated to a temperature between 400–500 °C, prior to casting aluminium L65 at a temperature of 700–800 °C.

E) Quality evaluation of casting. The whole casting process has been closely monitored and recorded. The casting results have shown that actua, thermojet and sanders models were the easiest to process, giving no residue after firing and producing good quality castings. The trueform model produced noticeable levels of ash after firing. This problem has been overcome with the castform models, which did not leave any residue after firing. All the RP routes produced sound castings, apart from the EOS polystyrol patterns where failure of the shell occurred during The pouring of the metal. There is always a risk of shell failure, even with conventional wax patterns, and it is possible that some unnoticed cracking had occurred during firing. It is notable that some ash residue was present after the quickcast models had been flash fired.

To assess whether the surface quality and feature definition of the RP models had a noticeable influence on the quality of the final castings produced, these were examined visually. It was found that, in most cases, the quality of the casting closely reflected the quality of the RP patterns used to produce them. Undoubtedly, the best surface finish and feature definition was produced from the sander models. Indeed, the castings were comparable with those produced from conventional wax patterns. The upward-facing surface of the castings produced from the actua and thermojet models were almost as good as those from the sanders patterns, but their undersides showed a poor surface finish due to the supports. The castform models produced a casting with a smoother surface than the trueform models with no visible stair stepping (effect of layer thickness), but there was a significant loss of feature definition. The castings from the SLA models showed stair stepping on the upward-facing surface and distortion on the underside of the pipe, due to the supports. The castings from the FDM models faithfully reproduced many of the flaws on the models, including the extruded tracks (just visible) and the start and finish of the tracks, particularly on the pipe.

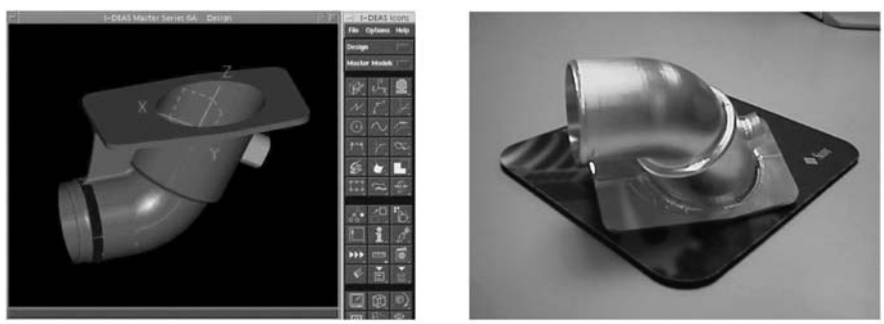
To add to the information gained from the visual inspection, surface roughness measurements were taken of both casting and models at three points. In the majority of cases, the surface roughness was greatest of the top surface of jet pipe. This is the angled plane where stair stepping is most prominent. Generally, the finish of the surface of the support base was the best, the only exception being the castform model. Another interesting result was that in most cases, the surface finish of the casting was better than the RP models. One potential explanation for this effect is that the ceramic shell and the cast metal cannot precisely reproduce the surface of the RP models, and this results in the blending out of some of the surface imperfections. The sanders, actua and castform models had the best surface finish. Surprisingly the thermojet surface finish was not quite as good. The trueform, SLA and FDM models all suffered from a poor surface finish, particularly the top surface of the jet pipe.

F) Discussion. It was very difficult to deduce any firm conclusions from the geometric inspection of the RP models. However, the work presented does provide some guidelines for selecting RP methods and models, especially when considering the geometrical tolerance requirements. It has been found that none of the samples showed errors that would give grave cause for concern. Where higher accuracy is required, it is common practice to add a machining allowance to the castings and many features on the final casting, such as the angle of the pipe, would normally be manually adjusted to comply with the required tolerance.

4.1.2 Process 1 – additional studies

To further investigate the findings from the work described in Sect. 4.1.1, other studies have also been carried out. The same manufacturing routine has been applied to the TRW inducer in Fig. 4, to select suitable processes and confirm initial findings.

The BAE Systems pipe elbow (Fig. 5) was used to confirm the quality of casting produced by the different rapid prototype routes, and for evaluating rapid injection tooling concepts. Tools for producing investment-casting waxes were manufactured using a variety of RE processes. These pipe elbow RE patterns and waxes produced from rapid prototype



(a) CAD Model (b) Machined Component

Fig. 5. BAE systems pipe elbow

Table 4. Summary of the main findings from the RE system evaluation trials

Process	Advantages	Shortcomings	Material	Applications
SLA Quickcast	Transparent parts. Good accuracy. Fine detail. Widely available. Relatively fast.	Material properties rarely match those of the final product. Difficult to drain resin from quickcast patterns for thin-walled parts.	Epoxy/acrylate photopolymer resins.	High-quality models and patterns for casting and tool manufacture.
Laser sintering castform	Wide range of materials. Higher temperatures. More durable models.	Slightly porous, friable surface. Potential for in-process distortion, particularly for thick-walled parts.	Nylon, polystyrene, thermo-plastic elastomer (TPE). Resin coated sand wax, stainless steel, etc.	Functional prototypes. Investment casting patterns and tooling. Direct production parts.
Laminating processes (LOM etc.)	Relatively quick and cheap for larger parts. Generally used for pattern making / large space models.	Z-direction accuracy problems. Layered structure. Absorbs moisture. Not suitable for thin-wall or small items.	Generally resin coated paper (limited trials with metal, polymeric and ceramic foils).	Large solid visual models. Sand casting patterns.
FDM	Simple to use. Robust parts. Range of polymeric materials.	Poor surface finish. Comparatively slow. Anisotropic material properties.	Generally ABS but other polymers now available, including PPS.	Visual and functional models.
3D Printing Z402	Quick and cheap. More robust than wax models produced by alternative concept modelling systems.	Poor surface finish. Poor dimensional accuracy/repeatability.	Starch or plaster – either wax or resin infiltrated.	Visualisation and concept models. Starch models have been used for investment castings but surface finish very poor.
MJM Thermojet	Very smooth upward surfaces. Good feature definition.	Evidence of support marks on models. Poor dimensional accuracy and repeatability. Models easily damaged.	Waxy thermoplastic.	Visual/concept models. Investment casting wax patterns.
Ink jet printing solidscape*	Accurate. Good surface finish. Fine detail.	Small parts. Very slow. Weak/brittle models.	Wax – blend of proprietary organic compounds.	Intricate patterns for tooling and investment casting.

* Formerly known as sanders

tooling were cast to enable a detailed analysis (Table 4). This detailed technical evaluation of the material integrity and dimensional accuracy of the pipe elbow has provided the confidence for BAE Systems to formally sanction quickcast (SLA), castform (SLS) and thermojet (MJM) models for use as sacrificial patterns in the manufacture of cast Class A flight-certified aerospace parts. The pipe elbow was also used to make direct comparisons between investment casting and high-speed machining options. Large thin-wall components were successfully manufactured using the SLA quickcast process to directly cast an impressive Euro Fighter Aft Shelf Fairing for BAE Systems, expanding the size envelope of components to 600 mm [21] that are regarded as being suitable for development using RE tools [BAE Systems report on the RAMAC (rapid manufacture of high integrity aerospace components) Programme].

4.1.3 General discussions

The research established the relative technical merits for each of the RE pattern and wax-tooling systems based upon the requirements for manufacturing Class A aerospace castings of varying size and complexity. An economic assessment was undertaken and this clearly identified the most appropriate manufacturing routes for production volumes from 1-off to 500-off. This forms an important element of the evaluation criteria in the process selection system developed in an intelligent agent system.

It has been found that selecting the most appropriate rapid prototype pattern route for manufacturing the pipe elbow in low volumes, cost and time savings of up to 40% and 60% respectively can be achieved compared to traditional methods. However, to maintain dimensional accuracy, considerable expertise is needed to assimilate aerospace castings requirements and the process limitations inherent within different RE systems [22].

Direct laser sand sintering technology has been applied to produce moulds for the manufacture of magnesium alloy and aluminium based castings. Magnesium is being used extensively for aerospace castings, and it was important to establish a viable method for manufacturing rapid prototypes. This process was evaluated by successfully casting a GKN accessory gearbox, a large thick-walled component [21, 23]. A technical evaluation at GKN helicopters confirmed that the process provided components suitable for initial product evaluation and can be adopted on a future gearbox housings development programme.

4.2 HSM

High-speed milling technology was undertaken using two components – the BAE Systems pipe elbow and the TRW impeller.

It was expected to obtain information allowing direct comparison between alternative manufacturing routes.

4.2.1 HSM of pipe elbow

A) Component description. The industrial component is the pipe elbow of BAE Systems, as shown in Fig. 5. This component is a small, thick-wall part used in aircrafts. It features a complex combination of several difficult orientation angles. If the base flat surface is used as xy plane of the component frame, the angle between the axis of the big pipe near the base and z-axis is 29.393, the angle between projection of the pipe axis on xy plane and x-axis is 2.294. The end surface of small pipe is 87.706° to xy plane. The thickness of the small pipe is 2 mm. The material is aluminium allow (L168).

B) Machining strategy. Due to the complexity of the geometrical features, there are the following challenges to produce such a component using HSM technology: (1) accurate alignment of multi-setups; (2) extra length cutting tools to cut deep features; (3) thin and curved wall machining; (4) difficult orientation angles; and (5) difficult fixtures.

To machine pipe elbow from block, a multi-axis and two setups are required. These are called Setups 1 and 2. To achieve the high accurate alignment of the two setups, the block must first be machined accurately. For Setup 1, there are two operation groups: machining of base flat surface and the big hole. For Setup 2, there are five operation groups: (1) Position 1; (2) Position 2; (3) small hole machining; (4) boss machining; and (5) cut-off. The cutting tools are: T1-SLDrill ∅10, T2-SLDrill ∅20 with R2, T3-SLDrill ∅12, T4-SLDrill ∅12 with R3, T5-Ball Mill ∅6, T6-D30 TA118 and T7-D20 TA118. The cutting tool diameter unit is in mm.

Table 5 lists the machining methods for all machining operations based on Bridgeport VMC1000 and CAMAND. Figure 6 shows the machining strategy.

Table 5. Machining methods, cutting tools and spindle RPM

Machining operations, R – rough, SF – semi-finish, F – finish, D – drilling, UC – undercut			Machining methods	Cutting tools	Rotation table B (°)	C (°)	Spindle speed rpm	Feed rate m/s	Machining time
Setup 1	Base flat surface	R							
		F	APM	Tl	87.706	90	10K	2.8	14 min21 s
	Big Hole	D	Drilling	T6	35.637		650	–	5 min
		R, SF, F	CF	T2	35.637	0	10K	1.6	10 min45 s
		UC	CF	T4	61.637		10K	1.5	2 min9 s
	Sub-total machining time						27 min15 s		
Setup 2	Position 1	R	APM	T3			10K	2.5	64 min35 s
		SF	APM	T4	87.706	0	10K	2.8	10 min42 min
		F	APM	T4&T5			10K	3.0	66 min47 min
	Position 2	R	APM	T3	0	0	10K	2.5	117 min30 s
		SF	APM	T5&T4			10K	2.8	15 min
		F	APM	T4			10K	3.0	63 min40 s
	Small Hole	D	Drilling	T7	87.736		650	–	3 min26 s
		R, S,F	CF	T4	87.706	0	10K	2.2	16 min35 s
					62.706	0			
		UC	CF	T4	87.706	20	10K	2.5	11 min
		UC			87.706	−20			
	Boss & Bore	R	CF	Tl	60.642	0	10K	3.0	2 min
		F	CF	T4			10K	3.0	1 min28 s
	Cut-off	F	CF	T3	87.706	0	10K	2000	6 min50 s
	Sub-total machining time						379 min33 s		
	Total machining time						6 hr46 min48 s		

APM – advanced projection machining; CF – contour finishing machining

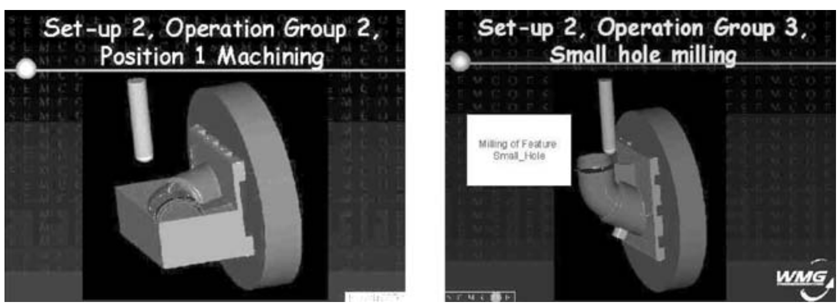


Fig. 6. Machining strategy of the pipe elbow

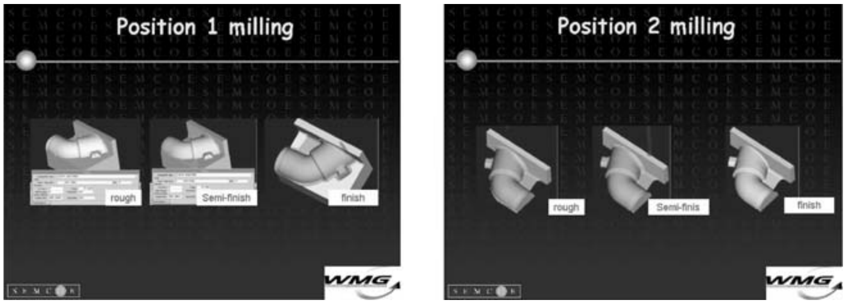


Fig. 7. CN code simulation verification

C) Part programming generation and verification. For this work, CAM software CAMAND has been used to generate part programs. Before the nc-codes are sent to machining centre, they must be verified. This verification has been done using CGTech's Vericut Simulation and Machine Simulation software, as shown in Fig. 7.

D) Machining. The Bridgeport VMC 1000 vertical milling centre was used. The maximum spindle speed is 10 000 rpm. Table 5 lists the real machining time, spindle speed and feed rate. The machining time has been recorded to as accurate as one second. The machined pipe elbow is shown in Fig. 5.

E) Inspection of the machined pipe elbow. RE has been applied to finish metrological inspection of this component. The machined part was first scanned using Renishaw Cyclone, then the point clouds were downloaded to surfacer for further processing to extract the required geometrical parameters, based upon the industrial requirements. Table 6 lists the nominal sizes, their tolerance requirements and the measured results. From the results, it can be seen that the component has been machined to the accuracy requirement level of industrial partners.

Table 6. Metrological inspection – results and analysis

Parameters	Nominal value & tolerance (mm)		Measured results	Status
Big hole inner diameter 1	59	+0.3 −0.3	59.26	OK
Big hole inner diameter 2	57.45	+0.05 0	57.49	OK
Big hole outer diameter	63	+0.3 −0.3	63.10	OK
Small hole inner diameter	48	+0.3 −0.3	48.16	OK
Small hole outer diameter 1	50.1	+0.2 0	50.04	OK
Small hole outer diameter 2	52	+0.3 −0.3	52.04	OK
Diameter of boss hole	11.8	+0.3 −0.3	11.00	OK
Diameter of boss	21	+0.15 −0.15	21.12	OK
Base length	128	+0.3 −0.3	128.24	OK

F) Discussion. From the HSM-based manufacturing methods proposed in this section, it has been found that the machining time of the pipe elbow was about 6 h 47 min using the proper machining strategy, part programming and cutting tools. Based on the simulation of machining using CGTech Vericut, this time could be reduced to about 3.5 h if a high performance CNC centre is employed, and machining strategy is further optimised.

The machining of the pipe elbow shows that HSM is a powerful technology to produce components with difficult geometrical features.

4.2.2 HSM of impeller

A) Component description. An impeller is a crucial component used to pump high-pressure fuel to aircraft engine control systems. The unit comprises of complex helical vanes and many small features on both surfaces of a thin disc, as shown in Fig. 8. It features a complex combination of prismatic geometrical surfaces and freeform surfaces. It is mainly consists of fourteen pairs of blades sitting on the two different conical surfaces with curvatures, many pairs of pockets with different surface features, and seven blades connecting the outer conical surface body and inner cylindrical body. The smallest fillet radius is from 0.4 mm to 0.6 mm. The width of the pockets is from 2.9 mm to 4.1 mm. The width of fourteen pairs of blades is 1.08 mm to 1.1 mm. The spans of fillets between the vertical surfaces of fourteen pairs of blades and conical surfaces vary due to the spatial surface nature. The surface number of CAD model at present is about 1800. The material is aluminium alloy (L168).

Due to the complexity of the geometrical features, there are the following challenges to produce such a component using HSM technology:

1. Accurate alignment of the two setups
2. Application of small cutting tools
3. Thin-wall machining
4. Small fillet radius.

B) Machining strategy. At Warwick Manufacturing Group, the Bridgeport VMC 1000 vertical milling centre was used. The maximum spindle speed is 10 000 rpm. This speed can be geared up to 30 000 rpm with a retrofit for small cutters of up to a diameter of 4 mm. CAM software is CAMAND.

After considering the challenges mentioned above, the available facilities and one or two batches for R&D purposes, it was decided that the impeller would be machined directly from

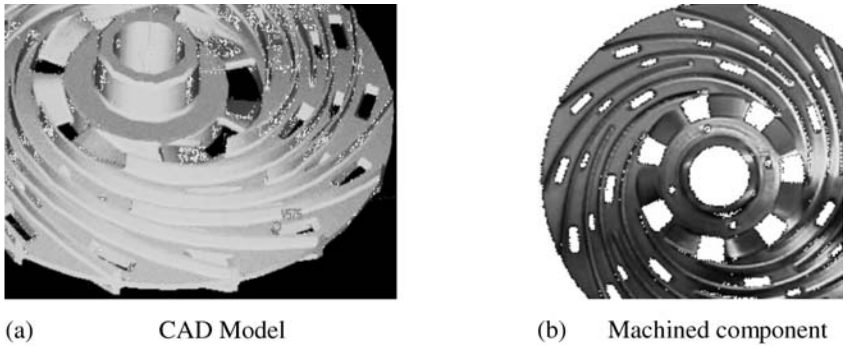


Fig. 8. CAD model of the TRW impeller

a block (for the real case of 50 or more batches, the stock should be machined using a turning machine to out-shape the impeller.) In machining the impeller from block, two setups are required: topside setup and bottom side setup. To achieve the highest accuracy in the alignment of the two setups, the block must first be accurately machined. For each setup, there are six operation groups: (1) topside surface preparation; (2) central boss or bore; (3) seven central blades; (4) conical surface; (5) fourteen blades (seven longer ones and seven shorter ones); and (6) thirty-five pockets on outer conical body. There are a different numbers of machining operations in each groups, as well as cutting tool changes. Table 7 lists the machining methods for all machining operations based on Bridgeport VMC1000 and CAMAND. Cutting tools are T1-SLDrill ∅12, T2-Ball Mill ∅8, T3-SLDrill ∅4 with R1, T4-SLDrill ∅3 with R1, T5-SLDrill ∅3 with R0.5, T6-Ball Mill ∅2, T7-SLDrill ∅4 with R0.5.

C) Part programming generation and verification. CAM software CAMAND has been used to generate part programs. Before the nc-codes sent to machining centre, they have to be verified. This verification has been done using CGTech's software,

Table 7. Machining methods, cutting tools and spindle RPM; feed rate and machining time

Machining operation, R – rough, SF – semi-finish, F – finish, D – drilling, CH – chamfering			Machining methods	Cutting tools	Spindle RPM	Feed rate MPM	Machining time
Topside setup	Topside surface preparation	R	Roughing	Tl	10K	4.5	8:17
		SF	APM	Tl	10K	4.5	12:17
		F	APM	T2	10K	3.5	18:01
	Central boss and bore	Boss F	CF + APM	T3	28.5K	2.4	2:07
		hole D	CF	T5	28.5K	1.8	0:33
		bore CH	CF	T2	28.5K	3.5	1:05
	7 central blades	R	APM	T5	28.5K	2.4	22:48
		F	APM	T6	28.5K	0.75	29:25
	Conical surface	R	APM	T3&T4	28.5K	2.0	51:43
		F	APM	T3&T4	28.5K	1.8	70:26
	14 blades	F	MDCM	T4	28.5K	1.8	18:03
	35 pockets	F	APM	T5&T6	28.5k	1.8, 0.75	41:33
	Sub-total machining time				4 h36 min18 s		
Bottom side setup	Bottom side surface preparation	R,SF and F	APM	Tl	10K	4.5	3:03
	Central boss and bore	R	CF	Tl	10K	4.5	1:23
		F	CF	T7	28.5K	3.5	3:24
	7 central blades	R	APM	T7	28.5K	2.4	21:26
		F	APM	T6	28.5K	1.8	38:30
	Conical surface	R	APM	T3&T4	28.5K	3.5	41:46
		F	APM	T3&T4	28.5K	2.4	40:30
	14 blades	F	MDCM	T4	28.5K	0.75	17:02
	35 pockets	F	APM	T5&T6	28.5k	2.0	34:55
	Sub-total machining time				3 h21 min59 s		
Total machining time					7 h58 minl7 s		

1) Cutting tool diameter unit: mm, APM – Advanced projection machining,
2) CF – Contour finishing machining, MDCM – Modified dual contact machining

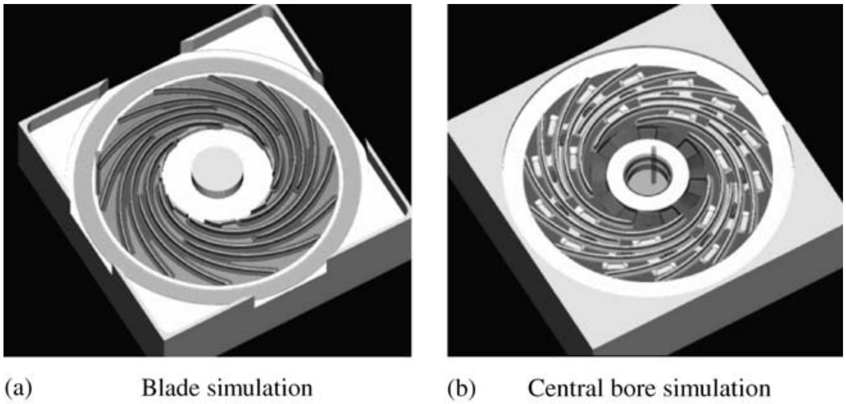


Fig. 9. NC code simulation and verification

Vericut simulation and machine simulation. Figure 9 shows the process of this verification.

D) Machining. Table 7 lists the real machining time, spindle speed and feed rate. It should be pointed out that real spindle speed and feed rate vary during machining; the figures listed in Table 7 are the estimated averages. The real machining time has been recorded to as accurate as one second. The machined impeller is shown in Fig. 9.

E) Inspection of the machined impeller. RE has been applied in the metrological inspection of this component. The machined part was firstly scanned using Renishaw cyclone, then the point clouds were downloaded to a surfacer for further processing to extract the required geometrical parameters, based on the industrial requirements. Due to limitation of paper length and number of features of component, the details of metrological inspection will be omitted. The focus will placed on the overall accuracy analysis by comparing the scanned point cloud with the original CAD model. Figure 10 shows mapping of point cloud and initial CAD surface model. Figure 11 shows the comparison of the point cloud with initial CAD surface model. It can be seen that the overall alignment of point cloud and CAD model is very satisfactory and the component has been machined to the accuracy requirement level of industrial partners.

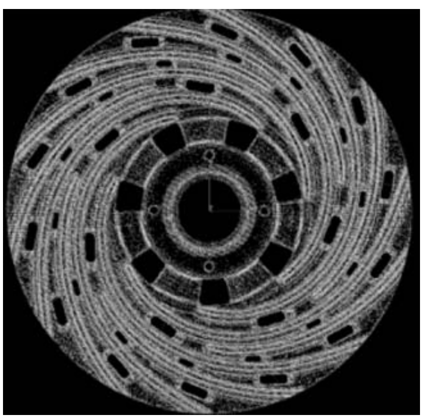


Fig. 10. Mapping of the point cloud and initial CAD surface model

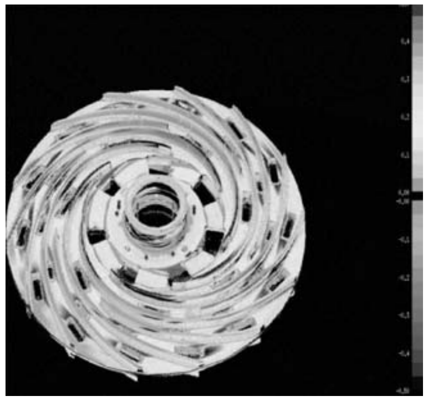


Fig. 11. The comparison of the point cloud with the initial CAD surface model

Table 8 shows statistical analysis results of the alignment comparison of the point cloud and CAD surface model. The number of points scanned is 511466.

F) Discussion.

1. The TRW impeller has been produced using HSM technology. The machining time was 7 h 58 min 17 sec. This time can be reduced to about 5 h if the machining strategy is optimised with a high performance machining centre.
2. The surface finish is relatively high quality and the geometrical (positional and angular) accuracy is very satisfactory.
3. HSM is a very good alternative rapid manufacturing method for developing high integrity components.

Table 8. Deviation analyses between the scanned point cloud and the CAD surface model

	Maximum	Average	Std. dev.
Positive norm.	0.49971	0.08148	0.04837
Negative norm.	−0.49998	−0.06390	0.05053

4. It is worthy to study the optimum combination of feed rate, spindle speed, depth of cut, types and sizes of cutters when small cutters have to be used to machining small surface features.

5 Application of RE

The developments associated with RE presented the greatest technical challenges. The algorithms for translating three-dimensional solid models into machining data is well established, but reversing the process to collect data from a machined surface to construct a functional solid model required complex mathematical computations. Scanned surfaces provide point clouds that need translating into triangulated meshes, and to be subsequently transformed into a three-dimensional solid model. These techniques were used extensively to generate solid models of RE patterns and cast components to provide comparison between initial design parameters and manufactured components, establishing a novel, robust process for measuring the geometry of complex curved components for inspection and technical evaluation. The commercial application and value of RE techniques was demonstrated by manufacturing an urgently required replacement thrust-reverser body. No drawings were available only an existing casting [24]. This component was scanned to produce a three dimensional solid model, surfaces were modified for shrinkage tolerances and allowances for machined surfaces, transformed into an SLA quickcast pattern, and cast in aerospace grade aluminium within five days. This represented a 60% savings in lead-time and 50% savings in design and manufacturing cost by adopting computer-based processes as compared to traditional methods [RAMAC report: rapid manufacture of high integrity aerospace components].

A further application of RE technology, which exceeded the original project objectives, was to use parametric cutter path data generated by a machine-tool control post processor to create a three dimensional solid model. The cutter paths were created from a component's key design features and the surfaces reverse engineered using point clouds, to create a functional three-dimensional solid model that could be used for design and analysis [25]. This model was intrinsically designed for manufacture and applying these techniques to a complex fuel system housing (Fig. 12) demonstrated the potential to reduce the manufacturing design lead-time in building test hardware by 55%. Subsequent manufacturing machining costs were cut by 30%. This was due to removing complex fillets, adopting standard cutting tools and exploiting extended cutter path geometries by improving modelling algorithms.

6 Cost-effectiveness and suitability analysis

The results of the above research have been analysed and were specifically compared with the present manufacturing methods used by industrial partners, to examine the leading-time, cost-effectiveness of the proposed methods. It has been found that:

1. It is very important to objectively evaluate different RP and RT models. This allows the various techniques to be rated against one another in terms of cost, accuracy, surface finish, and most importantly, their suitability for use in the investment casting process.

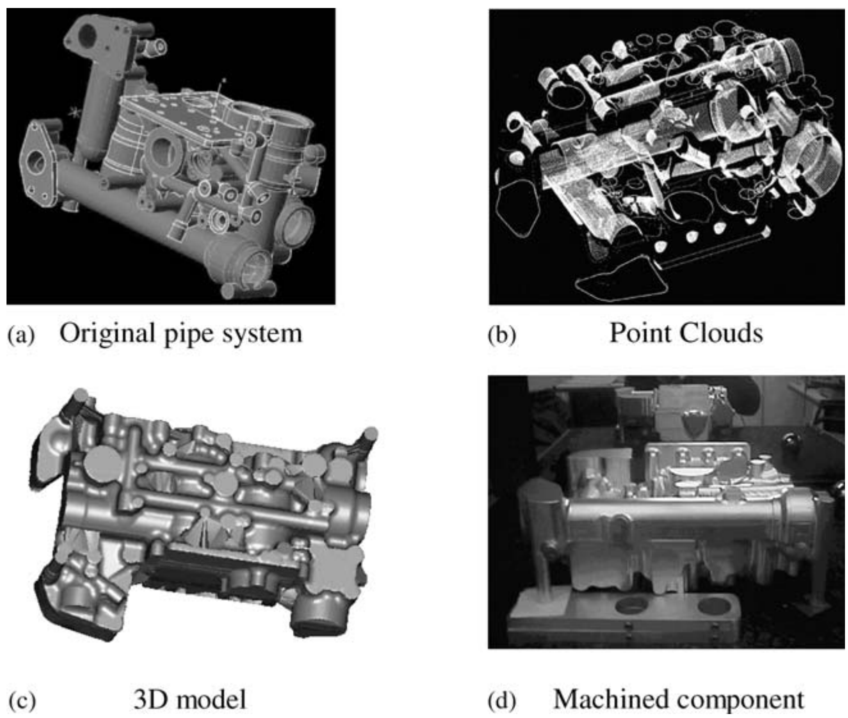


Fig. 12. Complex fuel system housing

2. The results of the work related to Process 1 can be applied to future programmes and will undoubtedly provide companies with substantial savings, particularly in terms of lead-time. The extent of savings will depend on the complexity of the components and number involved, but it would be reasonable to estimate a 50% reduction in lead-time for casting.
3. Work in Process 1 helped an industrial partner to carry out more work in investigating the suitability of the method, which indicates that component produced by this method can achieve a satisfactory standard for use on aircraft.
4. Findings from this project can be used to form part of a long-term RP strategy capable in the future of supporting all areas of business.
5. Findings have provided industry with a deeper insight into the behaviour and limitations of major RP and RT technologies for use in the casting process, thus giving a viable alternative method for the production of such components. These methods can be implemented across all aircraft functions, including concept demonstrators, legacy aircraft and aircraft on ground. It has allowed all partner companies to establish "best practice" methods of producing cast components and provides basic cost and time models on which to assess the real commercial benefits.
6. Work related to Process 2 has shown that machining volume parts using as small as one mm cutters would be relatively difficult and require expertise in part programming, but being able to produce prototype parts for early testing has enabled development lead-time to be reduced by 30%. Work on simplifying the vane curvature models has also improved the accuracy of the rapid prototyping models and will make this technology a viable method of producing low volume, complex cast components. The findings have demonstrated that HSM, used in conjunction with RE, is a viable new technology that will enable the aerospace industry to significantly reduce product introduction lead-times and subsequent development costs. This will make the UK's aerospace industry more competitive when bidding for new engine development programmes.
7. RE, HSM and 3D geometrical computation theory have been further investigated to propose a rapid design and manufacturing method. This method has been applied to fuel system housing, a complex part which must be machined from a solid. Findings have shown that the proposed method can be used to reduce design lead-time for building test hardware by 55%, and subsequent manufacturing machining cost by 30%.
8. RE, RP and RT have also been applied to develop the technology needed to manufacture components for early designs lacking drawings and tooling. The research findings can be further exploited by introducing this technique to facilitate the recovery of "legacy" units whose origins predate electronic data storage, and whose paper drawings are missing. The trial results of this method on the sample components – a missile valve blocks and a trim actuator body – have shown that the method will provide companies with the following commercial benefits:
    - 77% decrease in product introduction lead times;
    - 45% savings in non recurring product introduction costs;
    - 35% reduction in manufacturing costs for "one off" and low volume (up to six off) service parts; and
    - 50% decrease in production lead times for low volume parts.

7 Conclusions

This paper detailed a comprehensive set of theoretical investigations and industrial applications of computer-based, innovative manufacturing technology for high-integrity aerospace components. Two processes have been proposed based upon RP, RT, HSM and RE. A matrix of current aerospace components embracing critical design features common to the aerospace industry have been used to investigate the proposed processes and make comparisons between them. If applied to future development programmes, RP, RT, HSM and RE will provide aerospace companies the following benefits:

- 30% to 70% decrease in product introduction lead-time;
- 45% savings in non-recurring product introduction costs; and
- 30% to 35% reduction in manufacturing costs for 'one off' and low volume service parts.

The proposed rapid manufacturing processes have been proven to be cost effective means to produce high integrity components in production volumes. Examples include BAE Systems approval of RP patterns for Class A castings, RE and high speed machining of components and production of RP wax tooling.

The work presented in this paper will lead to a more competitive aerospace industry in the UK and maintain the world-class standards associated with this critical high-technology industry.

What's more, the finings can also be applied to rapid prototype development in the automotive and military industries.

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