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Advanced Manufacturing of an Aircraft Component (Fish-Head): A Technology Review on the Fabrication

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***Abstract*— The Airbus fish-head is machined using a 5-axis Computerized Numerical Control (CNC) milling machine, which consists of many complex shapes that are built into it. A conventional CNC machining requires tremendous effort in programming and investment due to the increasing in features complexity of the fish-head to be machined. An alternative method through advanced manufacturing processes namely vacuum casting, Fused Deposition Modelling (FDM) and three dimensional printing (3DP) is reviewed. The fish-head prototypes are manufactured through the concept of reverse engineering and rapid prototyping. The fish-head master pattern is digitized using a three dimensional laser scanner and edited using a surface modelling software to generate the Standard Triangulation Language (STL), which is common to most rapid prototyping (RP) machines. The fish-head prototypes are fabricated through FDM and 3DP using the STL data files, whereas the master pattern is used to fabricate silicone molds for vacuum casting. The quality of the prototypes is accessed in terms of dimensional accuracy and time to produce a single prototype. The dimensional accuracy is analyzed using coordinate measuring machine (CMM). The dimensional accuracy error is found to be less than 5%. However, all prototypes require secondary surface treatment processing in order to achieve the desired surface roughness quality. All three prototypes can be manufactured less than 24 hours per prototype. The advanced manufacturing processes allow parts to be fabricated similar to parts manufactured through CNC but at a lower cost and faster.**

***Keywords*— advanced manufacturing; vacuum casting; fused deposition machine; 3D printer manufacturing.**

I. INTRODUCTION

In a globalization era, creative and innovative technologies play an important role in the development of new products. Manufacturers constantly seek opportunities to shorten lead time needed to bring new products to market. An increasing competition in the world market has magnified this pressure in today's economy. Manufacturers must not only meet customer demands for functional products, but also reduce production cost to secure profit margins. In design verification and product development, a prototype modelling plays a unique role to improve product quality, shorten time to market and in-turn increases profitability. The quest for lower operating costs and improved manufacturing efficiency has forced a large number of manufacturing firms to embark on Advanced Manufacturing Technology (AMT) projects of various types. AMTs have been heralded as the new way for manufacturing companies to gain a competitive advantage [1]-[3].

There is a wide range of technologies employed by the manufacturers to produce prototypes including a Numerically Controlled (NC) machining and a Computerized Numerical Controlled machine (CNC), rubber molding, investment casting and others. CNC machining has been one of the most popular forms of prototype production due to few limitations on the material used for making the prototypes. This process offers industry a unique tool to fabricate functional prototypes for cost evaluation and design verification. However, a disadvantage often associated with machining is the lead time needed to prepare the required tooling before carrying out the machining operation [4]. Additionally, CNC machining is limited in its capabilities to machine geometrically complex surfaces or structures [5], [6]. A new perspective of making prototypes emerges with the introduction of rapid prototyping technologies such as Fuse Deposition Modelling (FDM), Vacuum Casting and 3 Dimensional Printing [7]. Both Reverse Engineering (RE) and Rapid Prototyping (RP) are emerging technologies that can play a promising role in reducing the product development time.

RE is commonly applied to the general process of recreating existing 3-Dimensional (3D) geometry in the computer. This 3D geometry can be in the shape of a real, manufactured object like a car or it can be any type of organic shape like a plant or a human body. Although many manufactured objects are now defined digitally using 3D modelling software, in many instances, the part may not be able to obtain the existing geometry digitally [8]. In RE for mechanical parts, often a digitizer is moved along parallel scanning paths and NC code is generated to move a cutter along the same 3D path. In effect, no model other than the raw scan data is used. Spline patches often fit to sampled position points. Geometry is usually represented in terms of surface points or collections of parametric surface patches to describe positional information. However, it is difficult to capture the high-level structure of the object.

The fish-head is an aircraft component for the Airbus A380 is currently manufactured using 5-axis CNC milling machine. This method however requires a huge amount of capital investment in term of acquiring the machine due to the complex features and programming. Other alternative methods which are more economical and easy to manufacture are sought to overcome such problems. New perspectives of advanced manufacturing processes that are considered in this project are FDM, Vacuum Casting and 3D printing.

A. *Project Objectives*

As mentioned previously, this project deals with alternative method in producing a fish-head component through advanced manufacturing methods. Therefore, this project has two specific objectives which are as follows:

- To manufacture a part with regard to Advanced Manufacturing methods that includes FDM, Vacuum Casting and 3D Printing.
- To investigate and review the feasibility of the alternative manufacturing method instead of the conventional CNC machining.

B. *Scope of the Project*

The attention of the project work is given to the applications of rapid prototyping in the aerospace parts or components. Comparison and review of these three alternatives of AMT will be conducted in order to assess the suitability of manufactured parts in terms of ease manufacturability. The project eventually provides the manufacturer an alternative method to the CNC machining that can produce a near net shape prototype, but at a lower cost and at a faster time. Thus, allowing more complex parts to be produced using these technologies in term of reverse engineering.

C. *Essential Factors in the Review*

Even though the fish-head is common to CNC machining, it is a good attempt to diversify the options of manufacturing processes. Technology review is one of the ways to select other manufacturing processes that could open a perspective in prototype manufacturing. The general attributes of RP can be put together as follows:

- A material additive process.
- Able to build complex 3D geometries including enclosed cavities.
- Process is automatic and based on a CAD model.
- Requires no part specific tools or fixtures.

The advantages of RP have opened up new opportunities for the manufacturers for faster product development through cost effective, simplified and in shorter product development time. This can be achieved through the integration of both RE and RP, thus allowing the reproduction of free form and complex objects can be made possible.

II. METHODOLOGY

The main objective of the project is to produce a prototype of a fish-head component through advanced manufacturing methods i.e. vacuum casting, FDM and 3DP. However, in order to fabricate a prototype through FDM and 3DP, the fish-head master pattern need to be digitized by using the non-contact CMM or 3D laser scanning. Later, it will be converted into an STL data file which can be used for FDM and 3DP. The input to the 3D laser line scanning is the fish-head master pattern and the surface color as this will influence the quality of the digitized fish-head point clouds. The point clouds are later edited through GEOMAGIC Studio 10. It is expected that the STL data files will influence the quality of the fish-head prototype fabricated through FDM and 3DP, as both processes relies heavily on the STL data files.

A. *Fish-Head Modelling Through 3D Laser Scanning*

The most direct method for creating a mathematical or electronic model of an object is to take traditional measuring devices such as micrometers, callipers, make measurements directly on the part and subsequently records the information on paper or in a computer. However, this requires extensive labor input and time consuming and not suitable for complex free form object. RE is the field of research involved with automating the process of creating computer models from physical ones.

Fig. 1 Fish-head scanning using Faro Laser ScanArm

In the project, 3D position digitizer such as non-contact coordinate measuring machine (CMM) is used. Non-contact CMMs can significantly decrease the time required for data gathering [9]. The machine projects a line or a spot of light and uses triangulation to calculate the range. For the project, a Faro Laser ScanArm3D laser scanner (Fig. 1) is used in combination with a GEOMAGIC Studio 10 as the software for editing the surface generated. The laser scanner provides a dense surface digitization of an object by combining the range sensor data and the positional data gathered from the encoders of the translation system. Provided the scanner is moved within its stand-off range, it will gather data points on a surface. If the scanner head is moved out of its stand-off range, no data points will be collected.

B. Fused Deposition Modelling

Fused Deposition Modelling is an additive manufacturing technology that builds functional prototypes and production parts layer-by-layer in engineering-grade thermoplastics. Building layer by layer makes it possible to create complex geometries unattainable with traditional manufacturing methods.

A plastic filament or metal wire is unwound from a coil and supplies material to an extrusion nozzle which can turn on and off the flow. The nozzle is heated to melt the material and can be moved in both horizontal and vertical directions by a numerically controlled mechanism, which directly controlled by a computer-aided manufacturing (CAM) software package. The model or part is produced by extruding small beads of thermoplastic material to form layers as the material hardens immediately after extrusion from the nozzle. The INSIGHT software enables the user to simulate the tool path and the time taken to complete the whole prototype built up before the actual part is fabricated through the FDM400MC machine (Fig. 2).

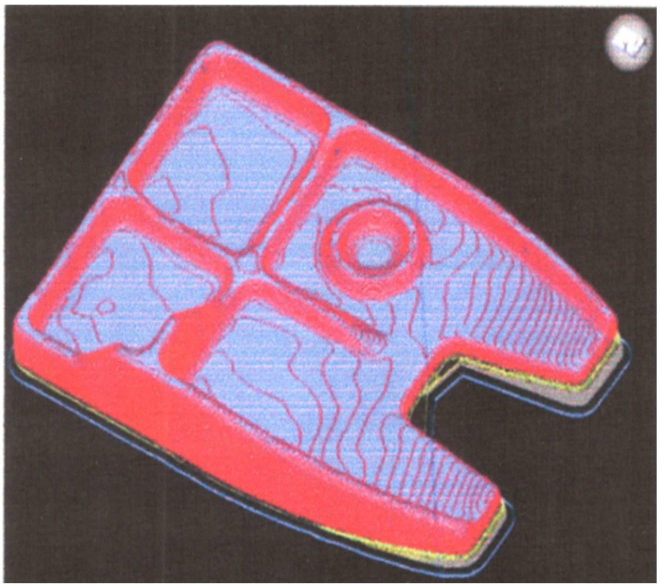

Fig. 2 STRATASYS INSIGHT simulated built profile of the fish-head prototype

C. 3D Printing

3D printer works just like a desktop inkjet printer, but instead of printing ink on paper the printer prints water-based glue onto a layer of powder, layer by layer. The fish-head prototype for the powder bed 3D printing method is fabricated using ZCorp ZPrinter 310 Plus machine. The ZPrinter 310 Plus machine has a built volume of 203 x 254 x 203 mm. The machine incorporates ZP150 composite built material which is white in color.

In 3D printing, the machine need for warming up to 38^{o}C above of the work environment. Then, prints the part layer by layer from the bottom of the prototype to the top. An ink-jet printing head selectively deposits a binder fluid to fuse the powder together in the desired areas. The printer first spreads a layer of powder in the same thickness as the cross section to be printed. Then, the print head applies a binder solution to the powder, causing the powder particles to bind to one another and to the printed cross section one level below. The unbound powder remains to support the part. The platform is lowered, more powder added and levelled, and the cycle repeats. Upon completion, the green part is then removed from the unbound powder, and excess unbound powder is blown off.

D. Vacuum Casting

Vacuum casting represents the current state of the art of creating accurate casts in large quantities and in the shortest period of time [10]. The entire process begins with a pattern and the mold making and duplication process. The master pattern from the mold is as shown in Fig. 3.

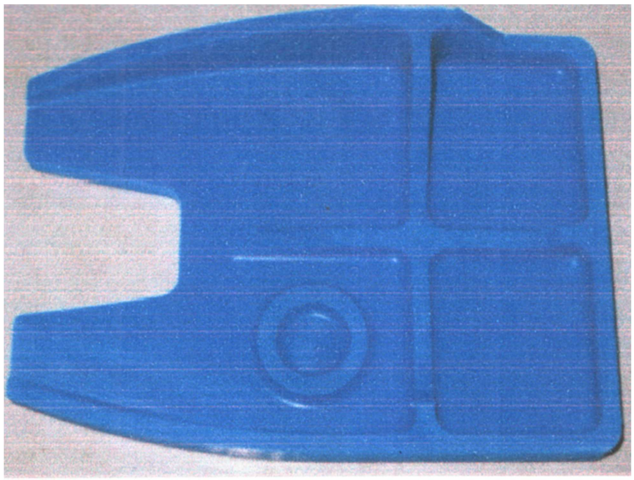

Fig. 3 Fish-head prototype pattern for the vacuum casting mold

The pattern is embedded on top of the modelling clay. For the project a two-piece mold is constructed. The modelling clay will act as a base for the pattern and also as a separator for the bottom mold. The master pattern is pressed into modelling clay, burying it halfway. To keep the mold halves aligned, four hexagonal nuts press into the clay. This creates cavities and later corresponding pins to lock the halves together. Next stage the riser, gates and vents are added to the pattern. A box made of plywood is built around the embedded master pattern.

The schematic flow of the overall project is shown Fig. 4. The whole duration and progress of the project is 3 months. The three dimensional (3D) digitizing of the existing physical fish-head master pattern is considered as a pre-requisite for the success of the project. Overall, 4 prototypes will be fabricated through the identified advanced manufacturing methods, i.e. vacuum casting, FDM and 3DP.

In this section, the analysis of the end results is presented and discussed. Comparisons between the fish-head master pattern and the prototypes are conducted and focused mainly on the geometrical accuracy and the speed to produce the prototype.

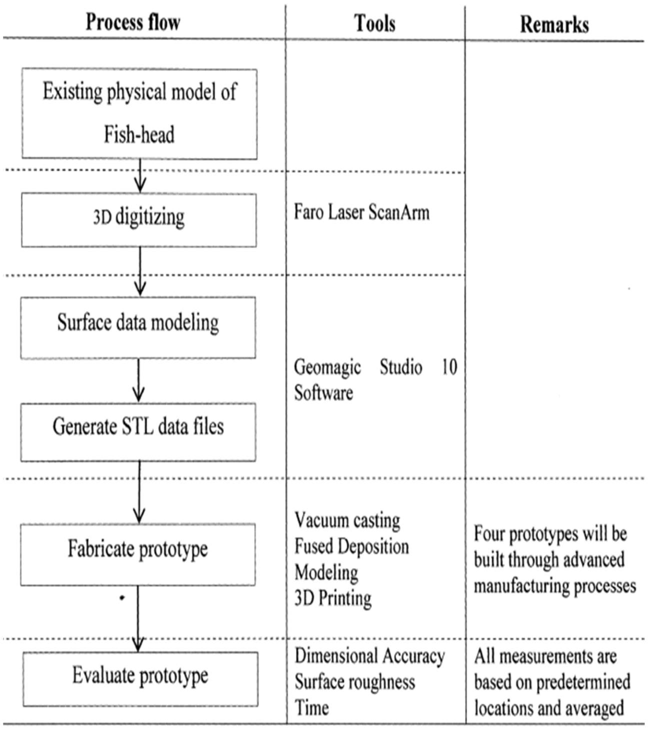

Fig. 4 Schematic flowchart of the overall project

III. RESULTS AND DISCUSSION

A. *Fish-Head Solid Modelling Through 3D Laser Line Scanning*

The fish-head is scanned by using the Faro Laser Scan Arm for the surface modelling of the prototype. The 3D laser scanner is used in the project as it makes possible to recreate an existing part of reconstructing its surface geometry. This technology enables to create an STL model of a part that has no design data. The Faro Laser ScanArm is a stripe type laser scanner. The laser scanner radiates a line of laser beams, called a stripe, onto the surface so that several points can be acquired at once.

In Fig. 5, the fish-head surface is painted white for a better reflectivity and diffusion for laser scanning purposes. As the higher the reflectivity and diffusion, the less error the system will produce [11]. The Faro ScanArm laser wavelength specification is at 660 nanometers (nm) and based on studies by [12], white is considered as a good reflector and a laser diffuser at this wavelength. The fish-head is coated in thin white coating with Magnaflux SPOTCHECK SKD-S2 Solvent Developer.

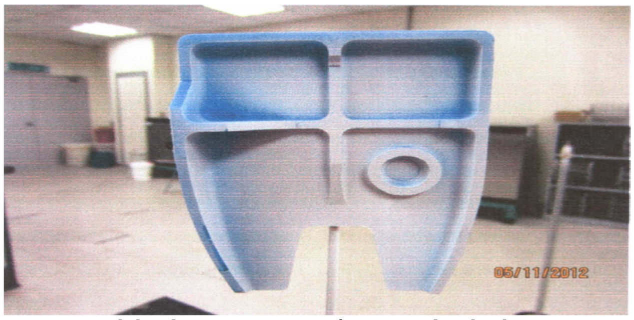

Fig. 5 Fish-head master pattern surface painted with white coating

B. *Fabrication of Fish Head through Vacuum Casting*

Room temperature vulcanization (RTV) silicone rubber (Alchemie RTV250) is used as the mold material in the experiments and a catalyst. Alchemie C250 is used in conjunction with the RTV250 silicone rubber to accelerate its curing during the mold fabrication process. These two compounds are mixed at the ratio of 10: 1 (10 part of RTV250 to 1 part of C250) or with a catalyst having 10% the weight of the silicone rubber for 6 to 7 minutes. Care shall be taken to avoid entrapping too much air during mixing. When the mixing is completed, the silicone rubber mixture is degassed at 23^{o}C to remove the air bubbles.

Depending on the extent of air bubbles in the mixture, the degassing process can range from 10 to 15 minutes. During vacuuming, the material will expand to approximately five times its original volume and collapse. It is at this point the material has been successfully vacuumed. After degassing, the silicone rubber mixture is poured into the casting frame to embed the master pattern. To avoid introducing air bubbles into the mixture when pouring, one method is to pour the silicone rubber into the casting frame from a high position relative to the frame which causing the silicone rubber to flow in a thin stream and allowing the air bubbles to burst on the way down. Another method is to tilt the casting frame and pour the silicone rubber into the higher end of the casting frame, which allowing it to spread over the rest of the casting frame and embed the master pattern. In this study, both techniques are used in conjunction to minimize air entrapment during pouring.

C. *3D Printing Analysis*

The 3D model of the fish-head is laser scanned and edited using GEOMAGIC STUDIO 10 solid modelling software and exported as STL file to the ZCorp software ZPrint Version 7.10. The system software developed by Z Corporation accepts solid models in SU, VRML, PLY and 3DS file formats as input. The input software format for ZPrint is STL.

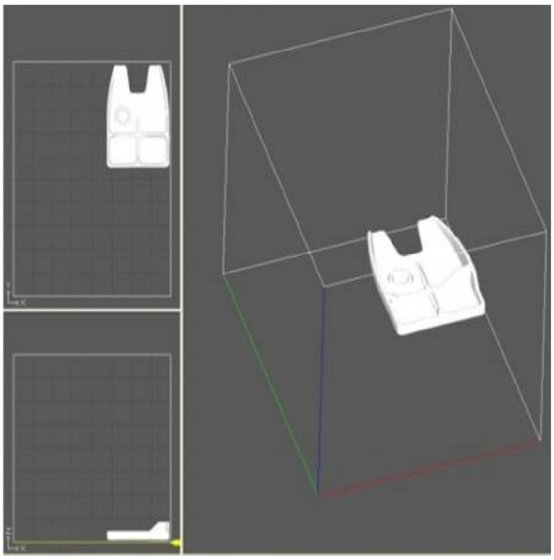

Fig. 6 Fish-head orientation on the Z3 10 Plus build table

The ZCorp Z-Print software breaks the STE model into individual slices and generate tool path for the fish-head layer by layer. The primary function of ZPrint is to cut the solid object into digital cross sections or layers, which creating a 2D image for each 0.1016 mm slice along the Z-axis [13]. The Z-Print software enables the user to simulate the tool path, the whole process layer by layer and the time taken to complete the whole prototype built up before the actual part is fabricated through the Z310 Plus machine (Fig. 6).

D. Fused Deposition Modelling (FDM)

The 3D model of the fish-head is laser scanned and edited using GEOMAGIC STUDIO 10 solid modelling software and exported as STL file to FDM software INSIGHT. The FDM400MC uses the Insight software to import the STL file. The Stratasys INSIGHT software breaks the STL model into individual slices and generate tool path for the fish- head layer by layer (Fig. 7). The INSIGHT software enables the user to simulate the tool path and the time taken to complete the whole prototype built up before the actual part is fabricated through the FDM400MC machine. The data are then sent to the FDM hardware for modelling.

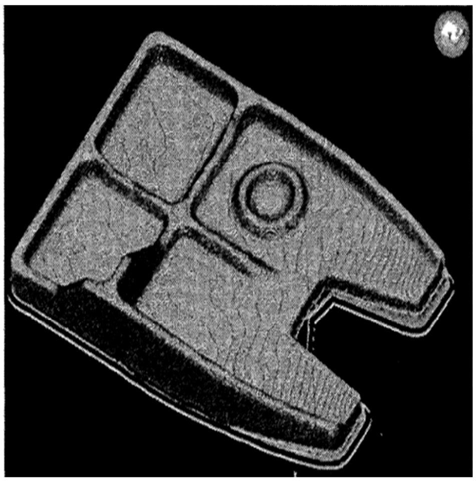

Fig. 7 Stratasys INSIGHT simulated built profile of the fish-head prototype

The prototype produced by the FDM processes is compared to the master pattern. The comparison includes the surface geometry, surface roughness and the time taken to produce one prototype. The dimensional accuracy and surface roughness were analyzed using coordinate measuring machine (CMM) and surface roughness tester respectively.

IV. CONCLUSIONS

In this section, conclusions are drawn from the project and recommendations are made for future works.

It is found that the vacuum casting, FDM and 3DP can produce the similar replication of the fish-head master pattern. This is because the dimensional accuracy error for all prototypes fabricated through the three advance manufacturing processes is less than 5%. Therefore, in terms of dimensional accuracy, the three advanced manufacturing methods are capable of delivering the highest quality products with high dimensional accuracy. However, there is slight distortion is observed on both FDM and 3DP prototypes.

Therefore, in terms of dimensional accuracy, vacuum casting is the preferred choice of manufacturing the fish-head prototype. It is also found that the dimensional accuracy of the FDM and 3DP is significantly related to the quality of surface digitizing and modelling through laser scanner and the surface modelling software. Laser scanners that are used as a measuring instrument, introduce errors in the 3D coordinates of each point cloud acquired. This is due to the object's surface appearance and reflection property. The laser scanner also introduces error components from the instrumentation itself.

Surface roughness has been always the crucial feature in the advanced manufacturing processes. All prototypes produced through the advanced manufacturing processes does not have the surface roughness quality as desired or similar to the master pattern, thus requires a secondary post processing machining to achieve the desired surface roughness quality This is often corrected by means of manual operations to the detriment of precision and the production times and costs, thus still greatly dependent on the skillfulness of the operator.

From the project, it is noted that through 3DP, the fish-head prototypes can be fabricated at the fastest time compared to FDM and vacuum casting respectively thus making it the most likely the advanced manufacturing processes to be adapted if speed is the main criteria of the manufacturer However, the main disadvantage of 3DP is porosity, which is not suitable for actual usage It is more suitable for conceptual prototype.

It is believed that this project can be further improved through these steps:

- To study the quality of the scanned and digitized data through laser line scanning. As this will affect the outcome of the STL data files that will be used further in the advanced manufacturing processes.
- To study the effect of the surface coating thickness for the purpose of reflectivity and diffusion in laser line scanning.
- This study can further be improved in determining the optimum coating thickness that is sufficient for the laser line scanning without interfering with the surface

actual thickness, due to the addition of a new surface during the surface modeling phase.

- The surface modeling of the fish-head can be further expanded to non-uniform rational basis spline (NURBS) using the GEOMAGIC Studio 10, as the current project scope focused only on STL data files conversion after the polygon phase in surface model editing.

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