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ENGINE DESIGN USING RAPID PROTOTYPING TECHNIQUES

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Abstract. *An internal combustion engine was designed in ProEngineer. The aim of this project was to develop a proposefull tool enabling the rapid design/development of the required engine. The first non-working model was built using a rapid prototyping machine. A visual analysis of the engine head model shown various fields where improvements could be made on the engine design. Therefore, the head was re-designed taking that into account. The second phase of the project involves the actual production of low cost direct casting moulds straight from the engine design. Design and manufacture integration now possible through Rapid Prototyping techniques enabled drastic reductions of the design-development-casting process effort.*

Keywords*: Rapid Tooling, Rapid Prototyping, Casting, Internal Comb. Engine, Mechanical Design*

1. Introduction

There is a European competition where small cars should minimize their fuel consumption during a trial. The competition is performed in a car track and the average speed is 30 km/h. In order to have the lowest fuel consumption the car should have a very efficient engine. The engine which design and production is herein described is intended for such a competition. The engine capacity is approximately 40 cm3 (Martins, Jasansky, and Ribeiro, 2004) and uses the Miller cycle concept (Martins, Uzuneanu, Ribeiro, and Jasansky, 2004). The engine (Fig.1) uses a special arrangement on the crankshaft in order to perform the Miller cycle in a very efficient way (the admission and compression strokes are much shorter than the expansion and exhaust strokes).

The referred engine will be one of a kind, which is to say that only one (perhaps a few) engine(s) will be built. Therefore the development of such an engine is completely different from the more conventional engine design. Its actual materialization constitutes a prototype. Prototyping is the process of building models of a product to test various aspects of its design pre-production, once slow and expensive, but nowadays Rapid Prototyping (RP) techniques allow fast production of prototypes.

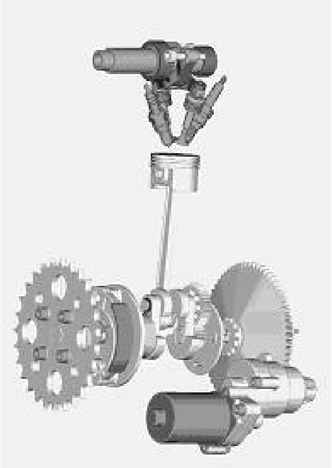

Figure 1. Miller cycle engine

Starting by using CAD facilities to model the design idea, a physical prototype can be obtained by processing the virtual CAD model using adequate manufacturing equipment. Such equipment should allow solid freeform fabrication, since most components of an engine have 3D complex shapes.

RP layered manufacturing techniques main advantage is their ability to form geometrically complex and intricate parts adding successive layers of material until the desired geometry is produced. On the other hand the materials that can be processed may not fulfil the final requirements the actual part must abide to. Also the attainable accuracy is far from the accuracy currently expected in mechanical construction.

When accuracy is the aim, machining must be considered. CNC machining also allows direct use of the virtual CAD model data, and a large number of engineering materials can be used. However, shaping by material removal imposes limitations to the geometry complexity to be produced.

Intricate complex parts can be achieved by foundry, i.e. pouring molten metal into a cavity which has the negative shape of the casting to be produced. Although the as cast accuracy is not enough for most of the technical uses, subsequent corrective machining of the features requiring improvement makes the technology adequate. It is then necessary to produce the moulds and cores needed to materialize the casting cavity.

The integrating of the techniques above referred, from a CAD model through a free form non functional model and its conversion into a cast part to be finished by CNC machining, offers the adequate materialization chain to obtain a functional prototype.

The head of the engine is one of the most crucial component as far as the engine efficiency is concerned. This work describes in some detail the most important phases of design and development of the engine head. The engine has some distinctive features such as twin spark plugs, swirl induced inlet manifold, squish zone on the combustion chamber and is liquid cooled. The latter feature (water jackets within the cylinder head) has a totally different reason for existence: as during the competition the engine is to be switched off for long periods (10 seconds on, 2 to 5 minutes off), it is very important that its temperature remains high during the off period. The water within the cylinder head has the purpose of increasing the thermal capacity of the head, therefore reducing its drop in temperature. Obviously, the outside of the head will be conveniently insulated. However, during engine test at the dynamometer the engine will be externally cooled using the water as the cooling media, in order to have a constant temperature operation.

Building the engine prototype will include virtual and physical modeling techniques. The following aspects must be taken into consideration:

- the virtual model built for design purposes will be used to make the actual prototype engine;
- the designer should have an early physical model of the engine, in order to check for design inconsistencies, to introduce modifications and choose alternative manufacturing techniques;
- the cost should be kept low.

The design was carried out in a CAD system, and 3D printing non functional prototypes where produced using the geometry so obtained. The same geometry was used to produce sand moulds and cores also using a SLS rapid prototype technique. An actual part was then produced by casting, using those mould and cores.

The search for the best engine implies the systematic improvement of its design, both in detailed definition and in manufacturing methods, including the testing stage.

2. Engine Project

From the requirements introduced above, the engine specification for this project is:

- capacity: 40 cm3, long stroke;
- valves: 2 (one inlet, one exhaust) at about 60º of each other;
- combustion chamber design: hemispheric with squish area;
- spark plugs: 2 ;
- valve train: OHC with finger (roller) followers;
- cooling: water jackets, just in the head;
- crank: epi-cycloid mechanism (to create the Miller cycle);
- fully digital injection and ignition.

The first design (Fig.2) had the intention of setting the head design, valve and spark plug location (including valve seats and guides), valve train outline (Fig.3), combustion chamber design and inlet and exhaust channels. The valve train is composed of a single central camshaft and finger followers. The design of the finger followers had the intention of reducing the height of the engine (they are bent) and reduce the friction (they have rollers on the contact with the cam). The engine was designed to be efficient and not to be powerful, so it will run at low engine speeds. Therefore the valves have small diameters for they will not impose great restriction on the air flow. Having small diameter also helps the inlet valve to promote turbulence, therefore increasing flame velocity and engine efficiency. The inclusion of two spark plugs also allows the use of very high compression ratio (we are expecting to reach 12:1 before the onset of knock). The combustion chamber is hemispheric and has a squish induced outer ring. The piston is a stock part and has a flat head.

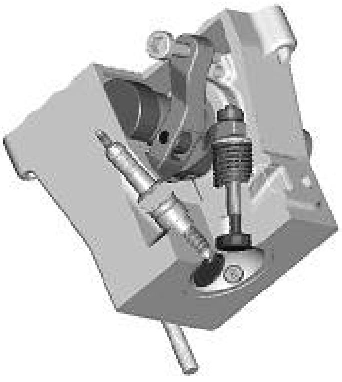

Figure 2 - Initial engine head design

Figure 3 - Detail of the cylinder head moving parts

A second design (Fig.4) was then conceived, which established finer details on the various components and introduced the water jacket in the cylinder head. The design of the water jacket involved the re-design of some components and their location within the head. The water volume should be enough for the engine to run during 10 seconds increasing its temperature by 5-10ºC. Because during the competition the engine will be thermally insulated during the period when the engine is switched off, the decrease in temperature should be similar.

Figure 4 - Second head design, with water jacket

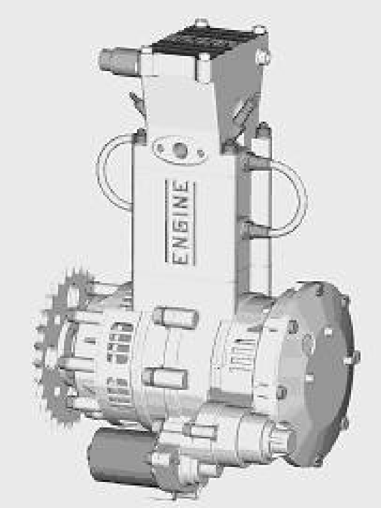

Figure 5 - Final full engine design

The third phase of the project was the full design of the engine (Fig.5), including cylinder, crankcase, crankshaft and starter. The crankshaft is of an unusual design (Fig.6). The intention is to produce a long expansion and a short compression (Fig.7), therefore creating the Miller cycle, already proven to be extremely efficient [1]. This is accomplished by using an epi-cycloid as crankshaft (Fig.8). Lubrication of the lower part of the engine will be by splash and the head will be lubricated by lost oil (during the engine operation some oil will be put in).

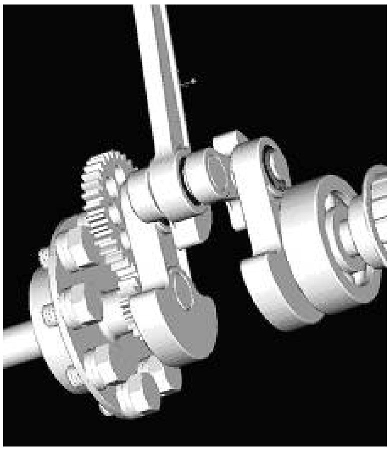

Figure 6 - Crank mechanism to perform the Mille cycle

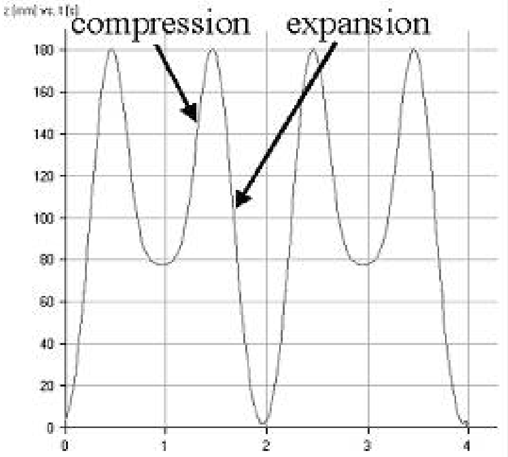

Figure 7 - Piston displacement for the Miller cycle engine

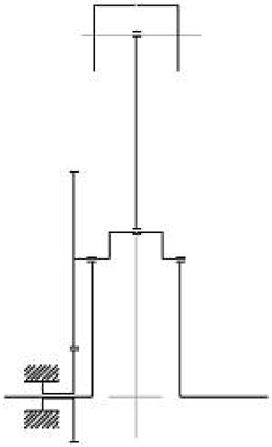

Figure 8 - Diagram of the epi-cycloid crankshaft

3. Building Steps

The overall engine case is to be made of aluminum. That includes the head of the engine which was chosen to be the first part to be produced. The material choice affects the manufacture of the component, since besides fulfilling service requirements it must simultaneously satisfy production feasibility and cost restrictions. Although a manufacturing technology cannot be established in a definitive way because new technologies or new technological variants emerge from time to time, casting is usually the correct natural choice to produce a single or a few functional metallic components having intricate geometry for it is versatile, allowing design freedom at low cost (Dickens et al, 1995,) Of course casting accuracy is not enough for a functional model; subsequent machining is then needed to obtain some of the desired features of a particular part (Barbosa, J., Monteiro, A., Pais, M., 1999). The features requiring more accuracy are then machined to fulfill design requirements. CNC machining provides that accuracy, as long as the cutting tool can reach the area to machine. Some features must be good enough for acceptance in as cast condition, eventually suffering hand finishing operations, as it is the case of the inlet and exhaust channels.

A problem remains: to pour the molten metal a cavity must be provided. Conventional technologies use a replica of the part, the pattern, to produced the cavity. Hollow features are produced using cores. The mould is produced by assembling the cavity and cores in which the molten metal will be poured through adequate channels built in the mould.

Rapid prototype technologies provide a method of mould production that is very convenient for use when single or a few components are to be manufactured (Saraiva et al., 2002). The pattern is not but the CAD model itself, and a virtual model of the cores and the cavity may be built. The entire mould can then be produced using adequate Rapid Prototyping equipment and technoques. The Selective Laser Sintering (SLS) system provides a solution, where resin coated sand is agglomerated by means of a laser beam in successive layers to form a physical model. Cores and moulds can be so produced. To guarantee the cleaning of the non aggregated sand occupying the inside space of the part or the filling channels, assemblies of partial components can be mounted to form the actual mould.

Average dimensional accuracy of the as cast parts is no better (nor worst either) than the accuracy obtained by conventional moulding processes using similar types of aggregated sand. The features demanding more accuracy have to be machined, as well as it is the case in conventional casting process.

Once again the existing CAD model will be useful, for CNC machining will take advantage of the virtual geometry provided by the CAD model.

4. Engine head actual building

From the virtual CAD model (shown in Fig. 2), the engine head was separated, and a 3D printing nonfunctional starch prototype as shown in Fig. 9 was produced. This prototype was intended to get the first sensorial contact with the part to be produced, and to check possible design inconsistencies, geometrical relationships between its features and permitted to establish the discussion about improvements. For instance, at this stage, decisions can be made about the holes that may or may not be prototyped. The thinner holes should better be drilled later, for the starch powder will be difficult to clean correctly.

The obvious benefit of rapid prototyping is building speed, but for product development the rapid prototype really delivers a better design communication tool. Objects can be formed with any geometric complexity or intricacy without the need of elaborate machine set-up or final assembly, reducing the construction of complex objects to a manageable, and relatively fast process.

The engine head was then redesigned to include a water jacket, also shown in Fig. 4, and then new 3D printing starch prototypes were been produced. Fig. 10 depict a sectioned engine head 3D printing prototype showing the layout of the jacket, including the inlet and exhaust track and the arrangement for the spark plug installation.

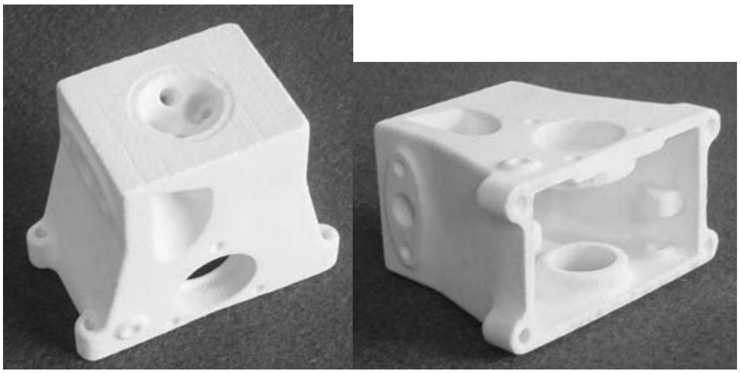

Figure 9 – Views of the 3D printing engine head prototype without water jacket

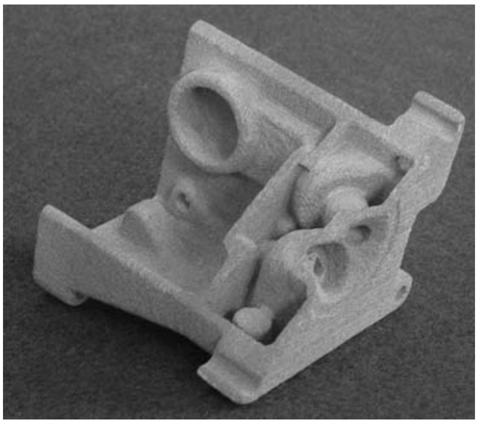

Figure 10 – Detail of the sectioned half head prototype showing the swirl inducing inlet

Fig. 11 presents the CAD model of the mould and core produced from the CAD model of engine head, which is also shown. These mould and core models were used to produce sand moulds and cores by the SLS rapid prototype technique (Fig. 12). The aluminum part produced by casting, is shown in Fig. 13, surronded by the mould components. Fig. 14 presents the cast part still keeping the filling system. It can be noticed a casting defect originated by defficient gas release during the pouring operation, which will induce modifications in the gating strategy, now under consideration, and so new improved design is being made for manufactoring reasons.

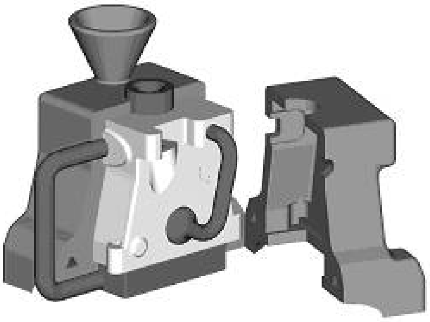

Figure 11 –Shell, core and part CAD models assembly

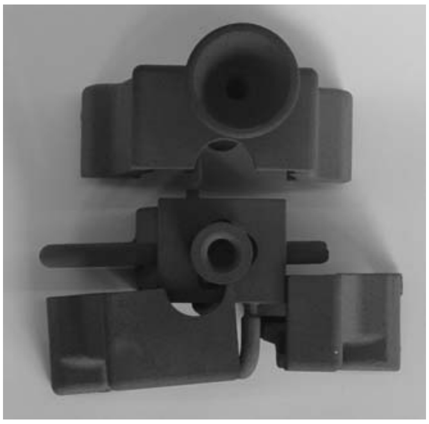

Figure 12 – SLS core, and shell prototypes ready to assemble the cast mould

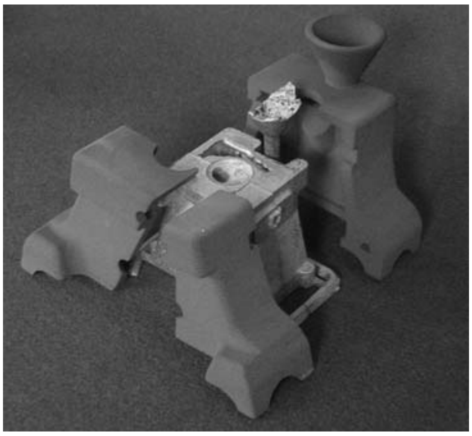

Figure 13 – SLS shell prototypes and aluminium cast part

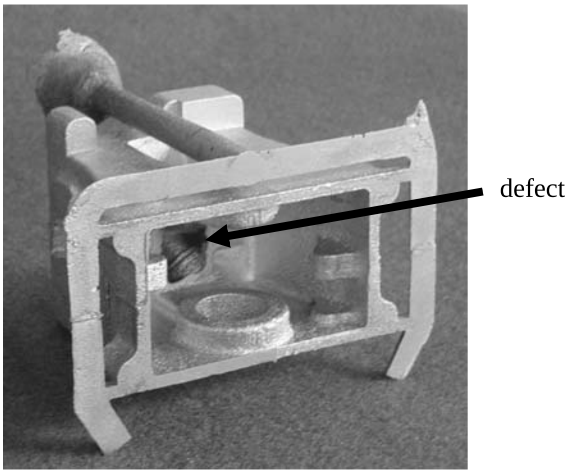

Figure 14 -Aluminum cast part with the gating system

5. Alternative possibilities

There is no single answer to which technology one should use. To produce a particular component, different technologies may be used. Likewise, the process one selects may vary by project and perhaps by component and no technology is right for every solution.

There is a family of casting technologies that use expendable patterns: the “lost pattern” casting technologies include the Lost Foam process, in which a polystyrene pattern is used, and the Lost Wax, process where the pattern is made in wax. In both methods the pattern is removed from the inside by temperature action, whatever during the actual pouring (Lost Foam) or in an adequate furnace prior to the pouring.

Rapid Prototyping technologies include a set of materials that can also be used as sacrificial pattern, the subsequent casting process being similar to the conventional expendable pattern processes. For example, Stereolithography (SLT) may provide a resin expendable pattern (Saraiva, et al, 2002), and Fused Deposition Modeling (FDM) may provide a polymer or a wax expendable pattern.

Complex geometry may also be divided into partial simpler ones, as shown in Fig. 15, so enabling CNC machining and subsequent assembling of expendable patterns. Polystyrene may be machined to produce the model in separate portions which, when glued together, will form a pattern to convert into a metallic casting by the lost foam casting process.

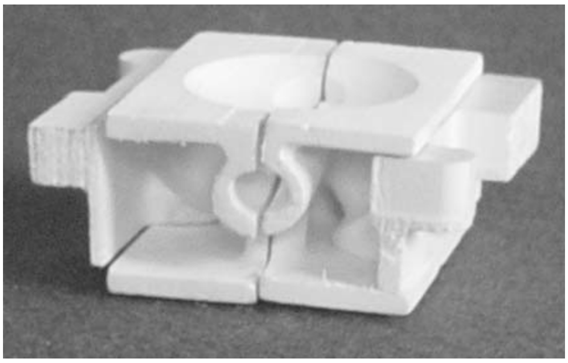

Figure 15 – Machiened polystyrene model to be used in lost foam casting

5. Future developments

New moulds and cores are going to be produced incorporating design improvements to minimize casting defects.

Also expendable machined polystyrene sacrificial patterns are going to be tested, as a manufacturing alternative route to obtain sound castings. The improved design to minimize the casting defects will be used.

A cheaper alternative to SLS to produce moulds and cores directly by Rapid Prototyping is under consideration, using the 3D printing equipment to aglomerate plaster or sand powders, aiming the production of metallic prototypes within 24 hours from the CAD file.

The other castable components of engine are going to be also prototyped in the next future.

6. Conclusions

A special purpose internal combustion engine was designed using CAD tecniques. This was an one of a kind engine designed for a specific aim (minimal fuel consumption).

Rapid Prototypes have been produced, allowing early improvements on the design, enabling a fast final design.

The use of Rapid Prototyping in the production of the casting moulds and cores made it easier to implement the design changes in the actual manufactured components. Modifications of the design were easily introduced into the actual parts.

Alternative manufacture methods are being considered to speed up the design/manufacture and lower its cost.

7. Acknowledgements

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