Motorsport Case study

The optimization of the lubrication system for a dry sump F1 gearbox

ABSTRACT

The case study will explain the optimization of the lubrication system for a dry sump F1 gearbox by experimental method, using RAPID PROTOTYPING and RAPID CASTING technologies.

The main targets are:

- Optimization of the oil pick up
- reduction of the flowing oil volume
- Reduction of the dissipated power

These main goals have to be obtained besides other issues, such as a low weight of the case since it is a suspended mass and a maximum overall stiffness. In fact the case is the major component for the suspension mountings and brackets and is connected to the engine: its stiffness is fundamental in order to get the minimum deflection, therefore providing the best car's stability and performance.

The chosen method is the optimization of the internal volume and the flow rate balance of the various G/box oil pick up, all this through the best manufacturing technology in order to leave maximum freedom to the geometry design for the internal casing dimensions.

FULL PAPER

CRP and Minardi have known each other for years, as are both protagonists in F1 world, as hi-tech partners and suppliers.

Founded by Gian Carlo Minardi in 1979, with the aim of competing in the European Formula Two Championship, the Minardi Team made its Formula One debut in 1985.
Minardi's best season to date was 1991, when its effective, Ferrari-powered chassis helped the team to claim seventh place in the final standings of the World Constructors' Championship. In 1992, Minardi switched from Ferrari power to the Lamborghini V12.
In 1999, the Minardi personnel line-up was further strengthened by the arrival of Cesare Fiorio as Team Manager and Sporting Director. As in 1998, the Faenza-based team was ranked 10th

in the final World Championship standings, in this case, courtesy of a very valuable point scored at the European Grand Prix by F1 "rookie", Marc Gené. One of the most satisfying aspects of the 1999 season was the excellent reliability of the M01, which helped its drivers to 10 top-10 finishes.
The 2000 campaign marked Minardi's 16th year in Formula One, and although the team did not succeed in scoring any points during the course of the season, it retained its tenth-place ranking in the World Championship, finishing ahead of the notably better-funded Prost Team.
In 2005 the Minardi F1 Team was acquired by Red Bull and in 2006 the new Minardi Team by GP Racing started a new adventure in Euroseris 3000. After the purchase of the Minardi F1 Team on the part of Red Bull, it seemed that the Minardi team was destined to disappear from the international scene, but fortunately it didn’t happen, thanks to the intervention of GP Racing,wanting to preserve the wealth of experience accumulated over twenty years of Formula One.

CRP has been instrumental in the success of many winning racing teams. From F1, to MotoGP, WRC (World Rally Championship), American Le Mans Series, Rally Raid (Paris –Dakar) CRP offers a high level of support throughout the entire project, including the manufacturing process.

What makes this company different are the partnerships they have formed with the different teams. CRP is involved at the earliest design and development stages and their innovative approach to the use of new materials and technology is widely recognised by the race car industry.
CRP Technology is therefore considered a unique service point for several different technologies and engineering activities.

The main activities are:

- **HQ & HSM CNC machining** (high speed and high quality machining with 3, 4 and 5 axis)
- **Rapid Casting** (lost wax casting with RP patterns) in Titanium, Aluminium, Steel alloys or Superalloys
- **Rapid Manufacturing and Rapid Prototyping** services
- **Rapid Manufacturing & Rapid Prototyping** composite materials production and sales
- **Total Quality Management**
- **R&D**: continuous research on materials like metallic alloys, plastic materials and new manufacturing processes development
- **Reverse Engineering**

In particular, CRP manages innovative projects, such as high precision titanium alloy castings and hard to work materials machining of complex shapes.

The Machining Department is therefore characterized by CNC milling centres, suited in particular to hi-tech materials machining.

THE EXPERIENCE

The Minardi gearbox

In **1998 CRP Technology began to work alongside the Minardi F1 team**, supplying them the engineering process, the manufacturing process optimization and the manufacturing of front and rear uprights: they began from the study of the **Titanium Rapid Casting process**.

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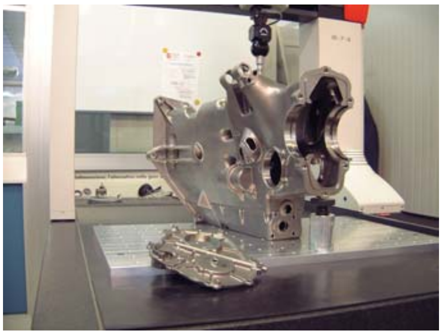
Rapid Casting is based on the combination of Rapid Prototyping technology, to manufacture the disposable pattern, and Investment Casting technology.
After the uprights, CRP and Minardi applied successfully the same technology to the Gearbox manufacturing.

CRP Technology was therefore the **FIRST to use Rapid Casting** for really hard to cast shapes (such as F1 uprights and gearboxes) and alloys (such as Titanium alloys).

Minardi Titanium Rapid Casting gearbox 2000



Minardi Titanium Rapid Casting gearbox 2001

The project

On the basis of the gearbox developed in 2003 and used in the 2004 season, Minardi started work on developing a new gearbox for the 2005 season.
The goal of the study was to optimise the interior structure but most of all its volumes.
The targets are numerous:

- reduce the quantity of oil used,
- improve gearbox lubrication
- reduce the power dissipated
- make the casting even more rigid and lightweight

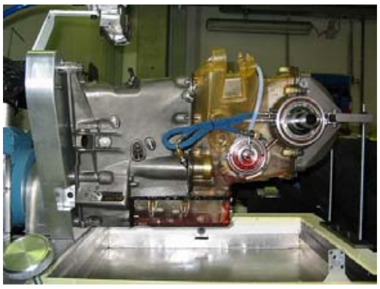
So Minardi's aim was to change the position of the gearbox oil pump from inside the sump to the outside of it which gives us a dry sump gearbox.

Gearbox 2005

Gearbox 2005

Minardi and CRP Technology have worked together on this project, preparing the road of evolution towards the new 2005 gearbox in **3 main steps**:

1. in the first step Minardi opted for SLA technology due to its transparent characteristics since the aim was to "visually" assess and verify the effectiveness of the gearbox lubricating system. But the results were unsatisfactory which was actually due to the technology used. To overcome these problems, Minardi turned to CRP Technology and the SLS Technology.



2. in the second step Minardi did, in fact, turn to CRP Technology to make the same gearbox with the SLS Technology using the composite material Windform® GF. It managed to complete the scheduled tests thanks to this.

3. the last step is about the implementation of the new cast gearbox using the Rapid Casting technique.

But let's look into the various steps in more detail.

Step 1

The first step started with some dyno tests with the gearbox case made with the sterolithography technique.
The result in SLA tested on the dyno does have a fundamental characteristic that puts it apart from the standard version: in fact the volumetric pump installed inside the oil sump was replaced with one installed on the outside.

Below is the method used for the first dyno test.

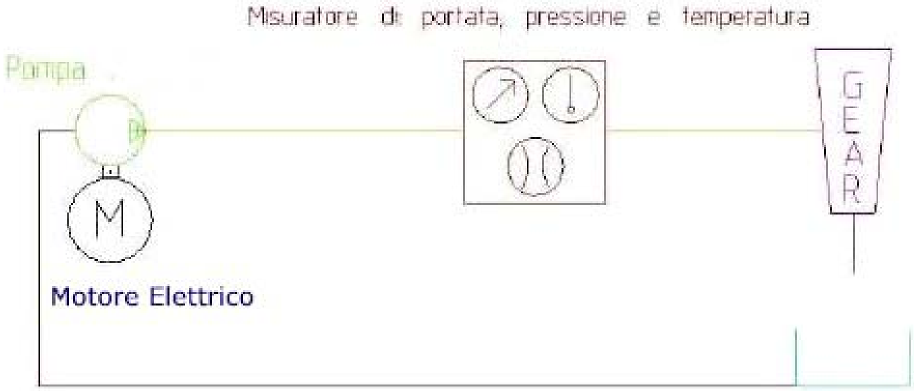


Figure 1: system diagram for dyno test 1

Figure 2: Gearbox mounted on the dyno
(traditional spacer in cast titanium, gearbox case in epoxy resin, rear traditional cover in cast titanium)

The dyno test, fitted out especially for this purpose, consisted of the following elements:

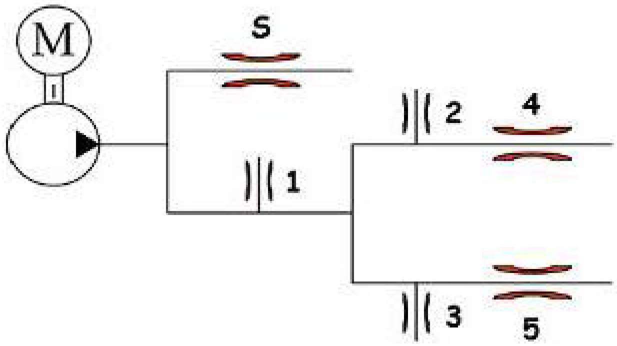
- the 2003 gearbox with the centre case obtained by means of rapid prototyping, driven by a 5 HP electric motor. The gearbox has no bottom oil sump so we have "dry sump" lubrication;
- volumetric pump with external gears driven by a 2 HP electric motor;
- dyno measuring instruments for flow rate, pressure and temperature;
- OPERATOR FLUID: hydraulic oil;

The aim of the test was to "visually" assess the effectiveness of the working of the gearbox lubricating system with an external volumetric pump and reduced capacity so as to reduce the power absorbed.
It was decided not to use the usual straw-yellow coloured lubricating oil but the bright red coloured hydraulic oil, in the vehicle's hydraulic circuit. From all the different kinds of oil available this one was chosen after comparing its specifications with those of the traditional oil. In fact, if we analyse table 1 we can see that the hydraulic oil, at a temperature of 30 to 35°, has the same kinematic viscosity as the usual lubricating oil at 60°C.

Hydraulic Oil Temperature	**Hyraulic Oil kinematic viscosity**	**Oil Lubrificating Traditional temperature**	**Oil Lubrificating Traditional viscosity**
35°C	43.31 cSt	60°C	42.38 cSt

50°C	23.21 cSt	80°C	23.46 cSt
65°C	14.67 cSt	100°C	14.50 cSt

Table 1: oil characteristics



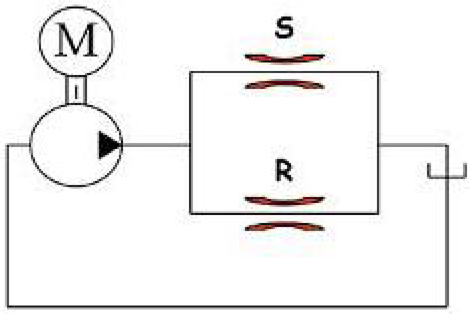


Figure 3a: diagram of the gearbox lubricating system (S = secondary shaft; 1 = forks and dogrings; 2 – 3 = third shaft; 4 – 5 = differential)

Figure 3b: simplified diagram of the gearbox lubricating system (S = secondary shaft; R = rear user point equivalent to user points 1, 2, 3, 4 and 5)

The main values obtained only at limited revs in virtue of the low mechanical characteristics of the case made with the stereolithography technique are given in the following table.

Engine rpm	Pump rpm	ΔP (Pressure)	Pump flow rate
2000 rpm	880 rpm	0,40 bar	1.07 l/min
3000 rpm	1320 rpm	0,69 bar	1.58 l/min

Table 2: experimental data collected during the test and dry sump (Toil= 30°C)

As you can see in the following pictures and considering that the limit of this test was dictated by the low structural characteristics of the material, we decided to keep drive shaft revs under 3,000 during the test.

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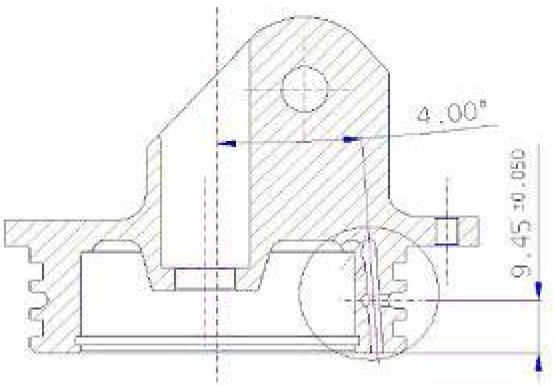
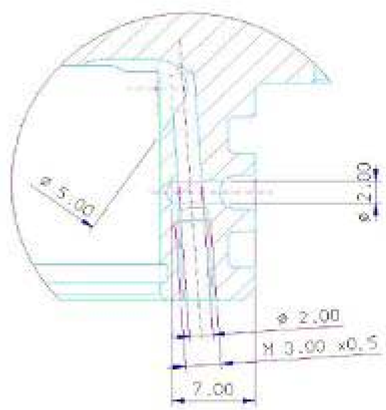
Figure 4: lubricating the bearings of the 3rd shaft – zoom of the two side Plexiglas covers with the gearbox at a standstill

Subsequent to a very thorough visual inspection/analysis of how the gearbox lubricating circuit works (see the pictures above), we were able to see how the flow of oil that lubricates the two bearings of the 3rd shaft is much greater than we had ever imagined.
In fact, in these pictures it is quite clear that the oil flowing by gravity from the two side bearings is far greater than what "falls" from the differential on the rear "bottom" of the case.

With the second test described here, we wanted to check the working of the system after a significant alteration had been made to the 3rd shaft user point. And, just as happened in the first test, we saw that the flow of oil to the bearings of the third shaft of the gearbox is much greater than what we had always thought. So what we want to do is try to reduce this flow of oil to the benefit of the differential user point to make it much safer.





The first change made to the system was, therefore, simply to reduce the size of this hole, of the oil passage on the cover of the 3rd shaft as illustrated in Figures above, which entailed reducing it from 2 mm to 1 mm. This reduces the oil runoff area up to ¼ of the standard value.

Engine rpm	Pump rpm	ΔP (Pressure)	Pump flow rate
2000 rpm	880 rpm	0,52 bar	1.07 l/min

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3000 rpm	1320 rpm	0,82 bar	1.58 l/min

Table 3 – experimental data collected during TEST 3 modifying the 3[rd] shaft and dry sump user point (Toil= 30°C)

If we compare the experimental data collected during test 3 (table 3) with those in table 2 we can see that we were successful in what we wanted to achieve, in other words, by modifying the oil passage of the third shaft (throttling the runoff areas) we have an increase in the system pressure at the same flow rate supplied by the pump.

The third test was to verify optimisation of the oil level with a **test using the bottom sump of the standard gearbox,** with the pump mounted inside the sump.

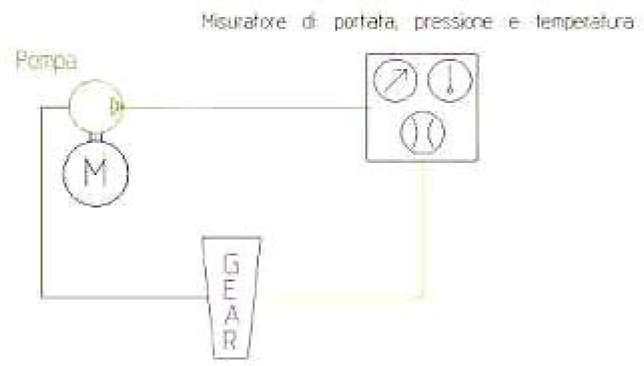


Figure 5: system diagram tested in the second set of tests

With the tests described below, we wanted to "visually" assess the effectiveness of the working of the gearbox lubricating system with different quantities of oil.
In Figure 7, illustrated below, the "lines" drawn on the outer surface of the case are clearly visible, indicating the different levels: each line corresponds to another ½ litre of oil added.

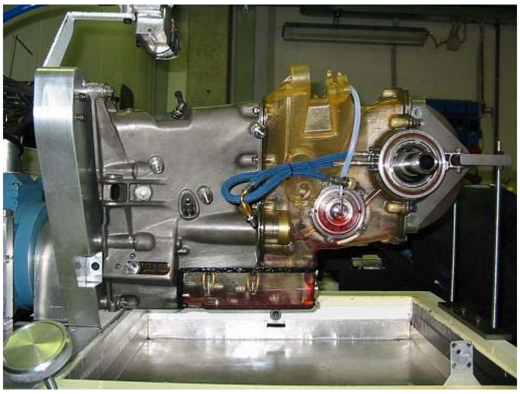


Figure 6: gearbox in static conditions with "only" 2 litres of oil inside

With the third test we had the confirmation that the system needs only 1 litre of oil to maintain circulation in the oil passage. The quantity of oil was increased for this purpose (Oil volume = 1.5 litres).

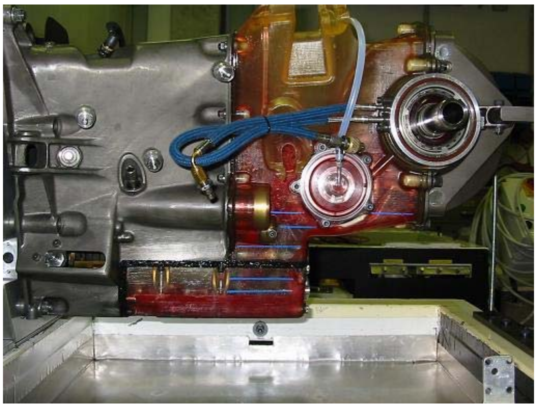


Figure 7: gearbox working (primary shaft rotation speed = 3,000 rpm) with 1.5 litres of oil inside

From the picture of Figure 8 it is quite clear that of all the oil put inside the gearbox case, 1 litre is circulating round the system while the remaining ½ litre, subject only to the force of gravity, stays at the bottom sump.
This confirms then that the minimum quantity of oil required to start the system is 1 litre and this quantity can in no way guarantee correct lubrication of the gearbox elements.

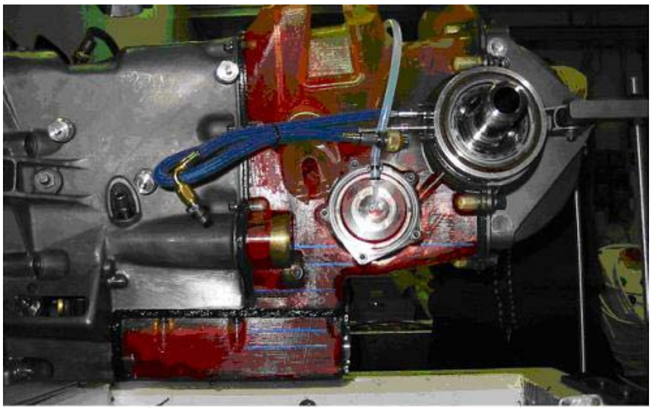


Figure 8: gearbox working (primary shaft rotation speed = 3,000 rpm) with 2.5 litres of oil inside

The purpose of the last test illustrated was to observe the working of the system under working conditions where, in effect, there are 2.5 litres of oil in the case. Figure 9 is a picture of the system where the primary shaft is turning at a speed of 3,000 rpm. If you compare this picture with those in the previous figures you will see how the quantity of centrifuged oil inside the case has increased with respect to the cases already examined. Due to the particular shape of the inside of the gearbox, the oil "centrifuged" by the interior elements of the gearbox reaches areas that are wet needlessly and which are too far away from the pump inlet orifice of the pump in the sump.

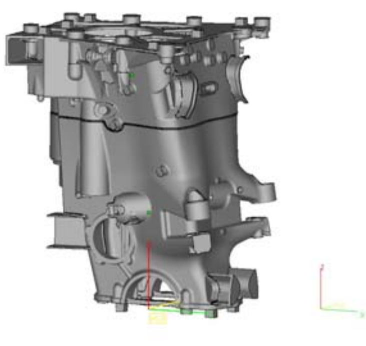
Overall results of Step 1

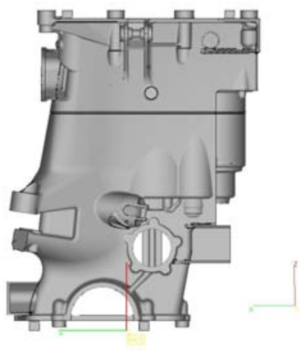
From the results of the tests illustrated above the following emerged:

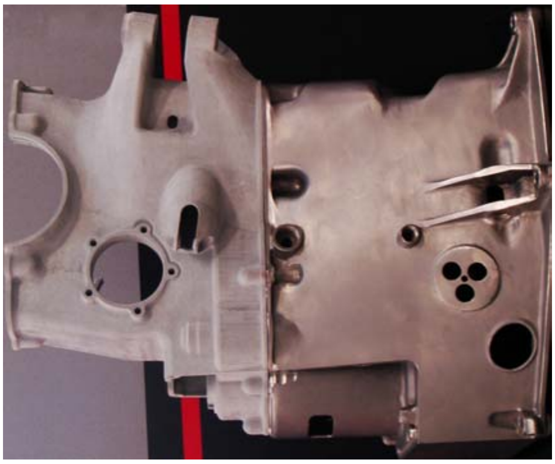
1. the standard rate of oil used to lubricate the bearings of the third shaft is far too much so we suggest modifying the oil passage of such user points until their inside diameter is 1 mm (see TEST 2).
2. In TEST 2, the external volumetric pump is enough to guarantee correct lubrication of all gearbox elements.
3. Thanks to the last test illustrated it was possible to show how the shaking inside of the oil is such to send the fluid to areas of the gearbox that do not require it. For this reason it is necessary to optimise the interior volumes.

Step 2

At this point it was fundamental to check whether or not the results and advantages obtained visibly could also be obtained **under conditions closer to real working conditions in terms of revs of the gearbox's primary shaft.**
Since the stereolithography technique, due to its limited mechanical characteristics, prevented us coming anywhere near the actual rotation speed which would have let us have a more correct and complete assessment of the situation, Minardi decided for the powder Laser Sintering Technology utilising material produced by CRP Technology, Windform® GF.





Thanks to the SLS technology it was possible to come closer to the actual conditions and thus make the necessary modifications to the shape of the gearbox for the final one for the 2005 season, taking full advantage of all the benefits we saw in the dyno tests with the SLA technology.

So Minardi began redoing the first dyno test, already described, taking engine rotation speed up to 6,000 revs, obtaining the values indicated in the following table:

Engine rpm	Pump rpm	ΔP (Pressure)	Pump flow rate
2000 rpm	880 rpm	0,40 bar	1.07 l/min
3000 rpm	1320 rpm	0,69 bar	1.58 l/min
4000 rpm	1760 rpm	1,02 bar	2.11 l/min
5000 rpm	2200 rpm	1,30 bar	2.61 l/min
6000 rpm	2640 rpm	1,59 bar	3.08 l/min

Table 4: experimental data collected during TEST 1 with a standard circuit and dry sump (Toil = 30°C)

These results show the correlation with the previous results and, therefore, the validity of the test.

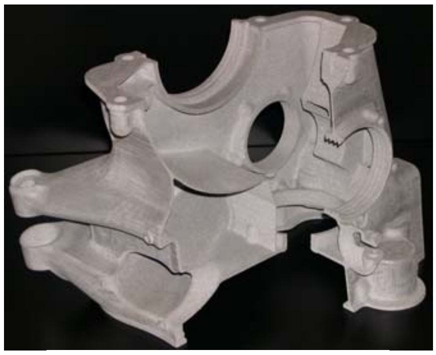
The next step is to verify the alterations made to the oil passage, using the SLS technology up to 6000 revs.

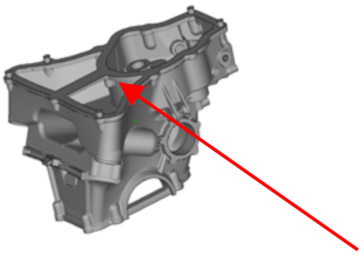
Engine rpm	Pump rpm	ΔP (Pressure)	Pump flow rate
2000 rpm	880 rpm	0,52 bar	1.07 l/min
3000 rpm	1320 rpm	0,82 bar	1.58 l/min
4000 rpm	1760 rpm	1,14 bar	2.11 l/min
5000 rpm	2200 rpm	1,49 bar	2.61 l/min
6000 rpm	2640 rpm	1,78 bar	3.08 l/min

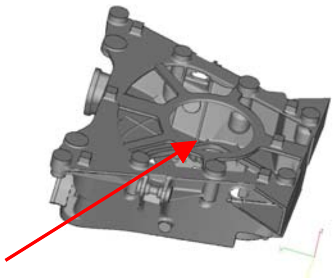
Table 5: experimental data collected during TEST 3 with alteration to the 3rd shaft and dry sump user point (Toil = 30°C)

With these tests we were more than confident in making and validating these alterations for the project of the new gearbox for the 2005 season.

At this point of the investigation the important aspect that is worthwhile pointing out is undoubtedly the reduction of the interior volumes with the aim of minimising the quantity of oil circulating around the gearbox which, as a result, means less weight, less heat and less power dissipated.
This was done by exploiting different interior shapes in successive evolutions which, after several bench tests, led to an optimum shape as can be seen in the exploded view of the main gearbox case in Windform® GF shown below.







Reduction of the interior volumes of the 2005 gearbox

Reduction of the interior volumes of the 2005 gearbox

Performance of the Windform material

The RP technology has therefore allowed us to assess in advance the highly important functions of the gearbox at the design phase, such as lubrication, structure shape, interior volumes to minimise the quantity of oil circulating and, consequently, assess the mechanical pressure pump and minimise its displacement.
All these advantages lead in the same direction – reducing the powers absorbed and the weight which are both essential factors for an F1 vehicle. But when this research involves vital parts of the vehicle and how they are going to work, one must be extremely careful with the choices made.
This approach to the problem was made possible thanks to the use of the Selective Sintering Laser technique, of which the CRP Technology in Italy was a precursor.

Step 3

Rapid Casting Technology was the next step used.

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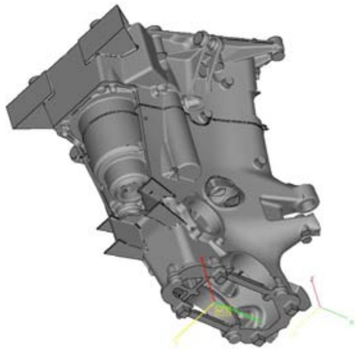
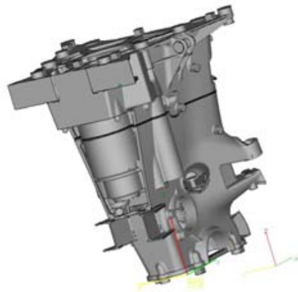
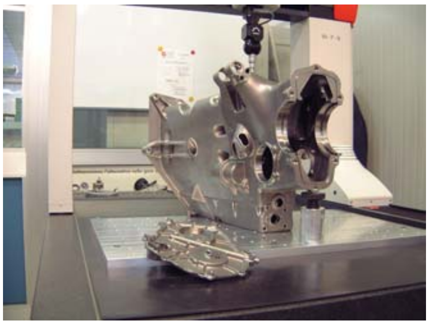
The RP technique was not exploited merely for this study but also used for the complete production of the gearbox case 2005.
Once all the geometries and surfaces of the gearbox were defined with CAD, a disposable pattern was then built in RP utilising the Rapid Casting technique with Castform® material.





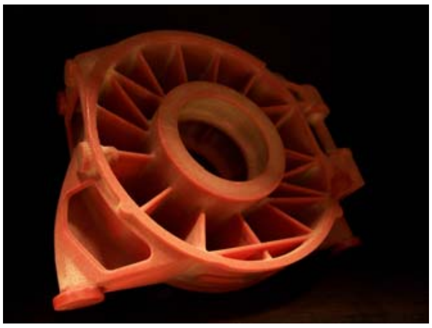
CastForm®, the material used nowadays for Rapid Casting patterns, was developed from the cooperation between DTM Corp. and CRP in 1998.
CRP began in fact in 1997 to study Laser Sintering technology to manufacture disposable patterns, using Polycarbonate and Trueform materials.

By the way, these materials were absolutely not suitable for Titanium alloys' pouring, despite they seemed to be perfect for steel and aluminium alloys. This was the reason why CRP and DTM decided to create a new material, developed for Titanium alloys casting. CRP's goal was to use Rapid Casting for very high performance parts, primarily for F1, therefore having very complicated shapes and geometries, and using the best alloy available for the casting procedure: **Ti-6Al4V**. Thanks to CastForm, the production of ash during the evacuation of the ceramic shell has been reduced: the ash, when in contact with the titanium, produces chemical reactions that damages the casting, and have therefore to be eliminated before pouring the cast metal in the ceramic shell.



Minardi Titanium Rapid Casting gearbox 2001

The RP disposable pattern is made by a consecutive overlapping of layers, using the Selective Laser Sintering technology. The system doesn't require any support because the piece is held up by the non sintered powders, therefore giving complete freedom of shape.



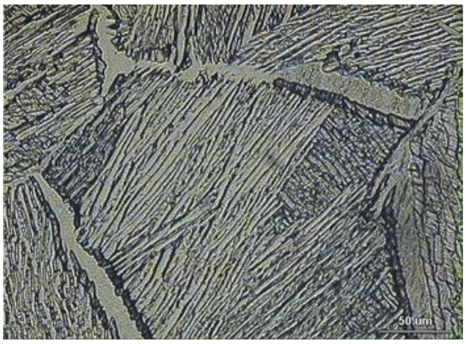
Disposable pattern: laser sintering and red wax infiltration

The Rapid Casting procedure is composed of a number of steps:

- A disposable pattern is made through RP technique and polystyrene material
- The pattern undergoes wax infiltrations (immersion and capillarity) to increase its strength (to avoid handling breaks);
- The pattern is immersed in a ceramic bath:
- Slurries and stuccoing and exsiccation;
- The lost pattern is evacuated: dewaxing with flash firing or in an autoclave and subsequent sintering of the ceramic shell
- Alloy casting with inductor or voltaic arc;
- pouring, cooling, reduction of the shell, shot peening, gate cutting, heat treatments

Example of disposable pattern, ceramic shell and casting

The casting structure is formed of an aggregate of grains or polyhedral crystallites which produce isotropy compensation, while in a solid metal they are anisotropic: it is obvious that isotropy has great advantages, for instance, FEM calculations are very close to the real behaviour of the part thanks to the isotropy of the piece.



Micrography in which it's possible to see the alpha-beta structure in the grain center and the typical annealed alpha structure at the grain border.

Moreover, Rapid Casting with laser sintered patterns allows complete shape conception freedom: thus reducing undercut and tool path problems during CNC machining.
It’s therefore possible to create the product along its mechanical stress axes, and to obtain a perfect reproduction of all details of the RP pattern, with tolerances and surface finishing of a very high quality (such as fully machined parts). It’s what we can call DFFF: Design For Functionality & Fun, thus allowing you to think about what you need and not how to machine it *(Design for Functionality instead of Design for Manufacturing).*

The Rapid Casting Procedure provided significant advantages:

For example:

- the possibility of maximum post-stress control of the components compared to carbon laminated parts
- durability and reliability of the detail (a casting is naturally isotropic for compensation)
- fewer design limitation
- the possibility to lightener (adding pockets) and get stiffer (adding ribs) the part during the racing season.

From a direct comparison between our solution and a gearbox produced in magnesium, the results are:

- 20-25% of weight saving
- approximately 20% of dimensions saving
- double torsional stiffness

less wear on the gears and lower power absorption, thus allowing the use of special lubricants, able to run at a higher temperature and with lower viscosity.

Conclusions

Undoubtedly, the collaboration with CRP Technology and its Rapid Casting technology has resulted in several advantages, such as:

- a reduction in the volume of oil and the possibility of using oil at higher temperatures, hence at a greater viscosity;
- lower power dissipated in the pump;
- optimising the shape meaning a smaller gearbox case;
- reducing gearbox case weight;
- greater torsional rigidity;
- the possibility of integrating the supports for the suspension couplings inside the gearbox case without having to put additional mechanical elements in between which is how it was done in the past in gearbox cases made in aluminium and/or magnesium alloy (therefore giving us a better overall tolerance, just the one structure which is even more "solid" and making the gearbox corner even lighter).