

Weight Reduction and Stiffness Enhancement Technology in Formula One Chassis Development

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ABSTRACT

When developing Formula One chassis, reducing weight while still satisfying the functions and requirements of each part was an issue for chassis design. The authors took into account the degree of contribution to circuit lap time, and found a balance between functions and weight reduction during chassis development. The method used consisted of reviewing materials and structures, and the weight of chassis parts was successfully reduced.

This paper introduces various examples of weight reduction.

1. Introduction

In chassis development, reducing weight and enhancing stiffness while satisfying the functions and requirements of each part is an issue that automobile design engineers are constantly working at in their daily development work, and Formula One chassis development is no exception.

Most racing car parts are related with the functions of accelerating, cornering, and stopping. Therefore, development placed particular attention on safety, and care was taken to develop parts that would not become factors resulting in retirement from a race.

In particular, parts that are directly linked to safety are given a Class A rank, and stress analysis is performed in the design stage to check that the prescribed safety factor is met before design release and manufacturing. Only the parts of which strength and durability have been confirmed by bench tests, can be

introduced to circuit tests. Finally, parts for which safety has been confirmed in the running state in track tests are introduced to actual races.

In this manner, much effort was given to maintaining safety and quality, even though one characteristic of Formula One chassis development is that time resources are always limited. Normal annual development consists mainly of parts development that aims to reduce weight by a few grams while securing the same stiffness as the previous model, or parts development that aims to enhance stiffness by a few percent while maintaining the same weight.

However, Honda aimed for weight reduction that far exceeded the bounds of this normal development, by introducing new materials and structures. In addition, emphasis was placed on reducing the weight of unsprung parts and parts located far from the center of gravity or in high positions, taking into account the map shown in Fig. 1 and other factors, from the standpoint of reducing

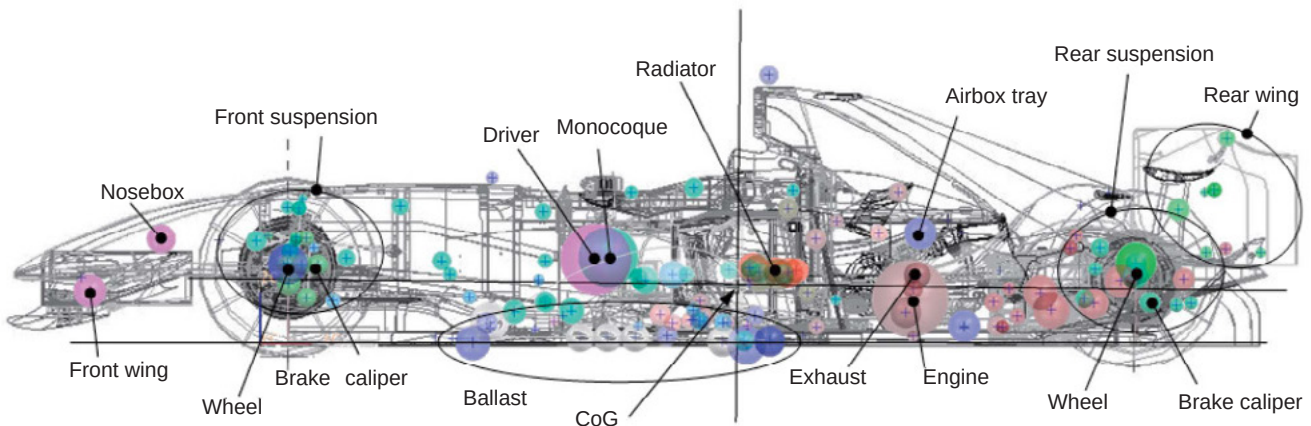


Fig. 1 CG_x versus CG_z plot for each component

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the moment of inertia. Furthermore, the contribution of chassis stiffness to performance was considered using evaluation standards that differed from those conventionally used for Formula One, and development also attempted to enhance the stiffness of key chassis locations including the engine.

2. Weight Reduction and Stiffness Enhancement of CFRP Parts

CFRP composites have high specific strength and specific stiffness, and are widely utilized in current Formula One chassis. Approximately 80% of chassis parts are made of this material, and most body parts in particular are made of CFRP composites.

Efforts to reduce weight and enhance stiffness in the body area focused almost exclusively to make the most out of the characteristics of CFRP composites. This was done by development of material or by applying new construction to the parts using small-lot production technology.

Weight reduction was investigated focusing on parts located far from the center of gravity, that is to say the nosebox, rear impact structure, and rollhoop, from the standpoint of reducing the moment of inertia. These parts are for crash safety, and must absorb collision energy by crumpling themselves. That requirement is stipulated in the regulations prescribed by FIA in such terms as the amount of energy absorbed, initial velocity, and rate of deceleration. We had to meet this collision requirement and reduce the weight at the same time while keeping the aerodynamically required shape and size, durability with respect to force inputs during circuit running, among other requirements. To realize this, a structure designed to increase the amount of collision energy absorption and the management of the manner how the part crumples during a collision was required.

CFRP parts are created by manufacturing a master model from a block of easily-machinable resin, and then producing a reverse mold by laminating pre-impregnated composites (prepreg), which are used to make molds, over this master model. The product materials are then laminated inside this mold, and formed in an autoclave. The manufacturing process involves a lot of manual work, so complex shapes and structures can be created.

However, being able to manufacture parts easily in a short time means that more time can be allotted to parts design, and more proposals can be investigated and tested. This can make a decisive difference when launching a new chassis in the beginning of each season, or when implementing a large-scale update partway through a season. Therefore, shortening the part manufacturing time is also an issue when aiming to reduce weight using new structures.

Typical examples of developing CFRP parts are described below.

2.1. Development of the Nosebox

The nosebox formerly used a sandwich structure (CFRP, aluminum honeycomb, CFRP) such as shown in

Fig. 2 (a) to secure shape stiffness with respect to front collisions. However, this meant that the energy absorption ratio per unit weight was small.

Therefore, the honeycomb was eliminated and a pillared structure with pipe sections in each corner was used as shown in Fig. 2 (b). This increased the energy absorption ratio while maintaining the shape stiffness, and achieved a weight reduction of 13% compared to the conventional nosebox.

In terms of manufacturing technology as well, eliminating the honeycomb enabled one-piece molding, which reduced the process time by 30% compared to the conventional nosebox. However, establishing predictive design technology took time, so parts with the conventional structure had to be made before manufacturing parts with the new structure. Changes to the external shape occurred repeatedly before all the parts with the new structure were completed, and therefore, these parts could not be applied to races.

2.2. Development of the Rear Impact Structure

The rear impact structure is a part that had a high energy absorption ratio from the beginning. However, when the external shape was stipulated by Formula One regulations, an even higher energy absorption ratio was required to prevent an increase in the weight.

CFRP absorbs energy by crumpling, so the more fractured the structure after a collision, the higher the energy absorption ratio. Focusing on this characteristic, a thin-walled structure with a window frame shaped cross-section [Fig. 3 (b)] was used instead of the conventional thick-walled structure [Fig. 3 (a)], to

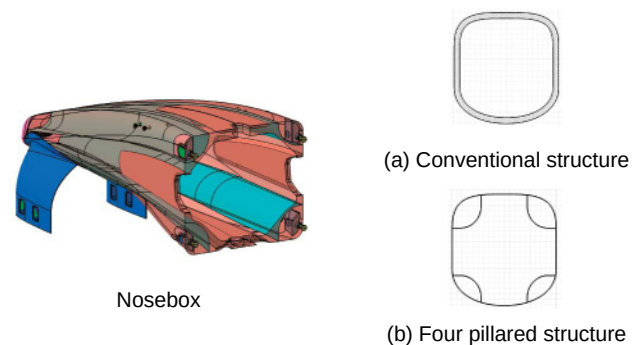


Fig. 2 Nosebox

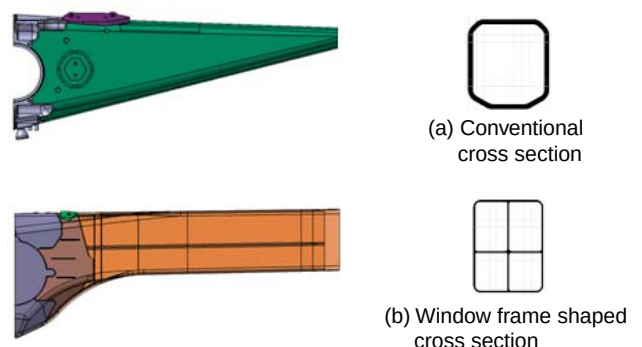


Fig. 3 Rear impact structure

achieve further fracturing of the components in the event of a collision.

This structure was created by laminating the window frame shape materials over a silicon mandrel, placing an outer mold containing the laminated outer shell materials over, and performing one-piece internal pressure molding.

The new structure achieved a 28% weight reduction, and was applied to races while continuing to evolve the design to more aerodynamic shapes every year.

2.3. Development of the RollHoop

The rollhoop must protect the driver's head in the event of rollover, and secure a sufficient air intake area for the engine. In addition, an aerodynamic external shape with respect to the rear of the chassis is also demanded.

A pentagonal shape as viewed from the front was introduced to reduce thickness and weight while still satisfying the above requirements. Within this structure, the roof lines of the pentagonal shape were set against to the load direction as stipulated by Formula One regulations. A thinner rollhoop that meets the requirements was successfully developed by increasing the load resistance of these portions to reduce deformation (Fig. 4).

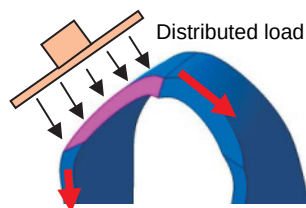
This reduced the weight by 18% compared to the conventional rollhoop, and we were able to apply this new rollhoop to races. In addition, the shape of the connection with the monocoque was also reviewed when switching the monocoque, which achieved another 16% weight reduction.

As engine development advanced and it became possible to reduce the aperture area, the next step was thought to be to increase the sectional area of the rollhoop to further reduce weight. The new design received loads with a planer surface, and weight was reduced by making use of the shape stiffness of the larger section, using a lightweight core (Rohacell)(Fig. 5). Prospects for lamination were obtained through simple investigation using past results, and the maximum load was predicted by fracture propagation analysis using a nonlinear analysis tool. In this way, the new rollhoop was designed. A structure that does not fail even when subjected to the regulation load was achieved by efficiently distributing the load over the entire structure.

This realized a weight reduction of approximately 20%, and the new rollhoop was applied to races.



Fig. 4 Pentagonal rollhoop



2.4. Development of the Engine Cover

The weight of exterior cover parts such as the engine cover (Fig. 6) must be reduced to the greatest extent possible while realizing aerodynamic functions. Therefore, as long as the part stiffness is kept by the shape, a sandwich structure with the minimum layers is used.

Weight was further reduced by making the CFRP materials that comprise the inner and outer shells of this sandwich structure as thin as possible. This was achieved by using a new material developed jointly with the material supplier, and by applying lightweight resins. This new material was an open fiber material made by spreading carbon fiber yarn into a flat, thin layer, making the fibers into a plain fabric, and then soaking the fabric in resin to create a prepreg. This realized a molded thickness half or less than that of normal materials.

As a result, the engine cover weight was successfully reduced by 60% in the qualifying specifications. To achieve durability, applied areas are modified, and the part with open fiber material was put in to the race specifications.

This material was also used to laminate various other external cover parts, and contributed greatly to reducing the weight of non-structural chassis parts.

2.5. Development of the Monocoque

Clarifying how chassis stiffness contributes to vehicle dynamics performance was a major issue. An attempt was made to enhance vehicle dynamics performance by increasing the stiffness of the joint between the power train and the chassis, and by using the airbox mounted on top of the engine as a stiffener, but an increase in performance could not be confirmed.

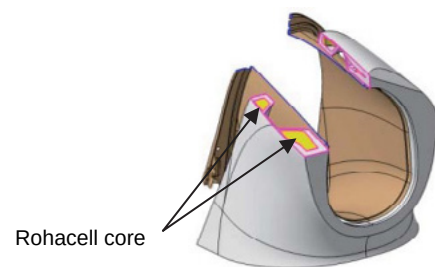


Fig. 5 Rollhoop structure



Fig. 6 Engine cover

Therefore, it was hypothesized that the degree of contribution of stiffness to vehicle dynamics performance is influenced more by the local stiffness of the suspension mounts than by the overall stiffness, and the monocoque weight was reduced with the sole restriction of equivalent local stiffness.

Figure 7 shows the weight reduction methods.

- Reinforcing materials were eliminated by allowing a 20% drop in the overall torsional stiffness.
- Exclusively developed side panel materials were applied.

The specifications were investigated using the local stiffness evaluation method employed in production car development, and the suspension mounts were reinforced as shown in Fig. 8. This showed that the weight could be reduced by 6.5% and the center of gravity lowered by 2 mm compared to the conventional specifications.

Track tests were performed to compare the new specifications with the conventional specifications. The results confirmed that even when the overall torsional stiffness is lowered, as long as the suspension mount stiffness can be secured, there is almost no effect on steering stability. Therefore, a monocoque that reflects these specifications was applied to races the following year.

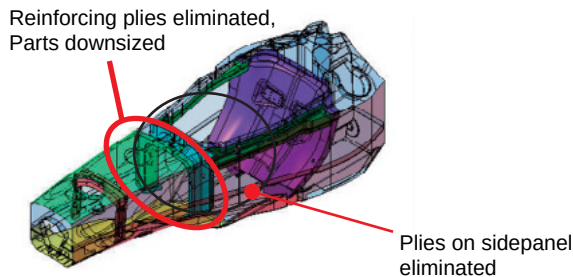


Fig. 7 Weight reduction method

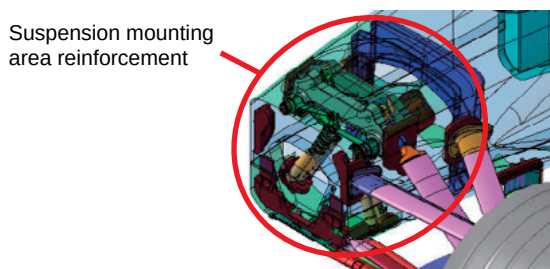


Fig. 8 Reinforcement method

3. Weight Reduction and Stiffness Enhancement of Functional Parts

Weight reduction and stiffness enhancement of functional parts such as the suspension, steering, axles, brakes, fuel system, radiators, and exhaust pipes is described below.

Development of these parts pursued part performance that enhances vehicle dynamics performance. This

included maximizing tire performance by optimizing the suspension geometry, controlling ground contact load by tuning the spring and damper systems, optimizing the power steering assist characteristics, optimizing the steering variable gear ratio, developing brake cooling technology that uses dynamos, reducing fuel sloshing, and so on.

On the other hand, the Formula One car weight is prescribed, so it was also important to reduce part weights to help lower the center of gravity and increase the freedom of longitudinal weight distribution using ballasts. The authors constantly set goals to promote the simultaneous achievement of both performance and reduced weight.

Various examples of developed parts are described below.

3.1. Development of Suspension Parts

3.1.1. Development of anti-roll bars

Figures 9 and 10 show schematic diagrams of the suspension systems. The anti-roll bar is a spring that acts only during rolling, and is a key part that controls the rolling angle when cornering, and also determines the longitudinal balance of rolling stiffness. In the conventional structure, the rocker arm acts on the torsion bar via links as shown in Fig. 9, and the mechanism is such that in the reverse phase (roll), the right and left

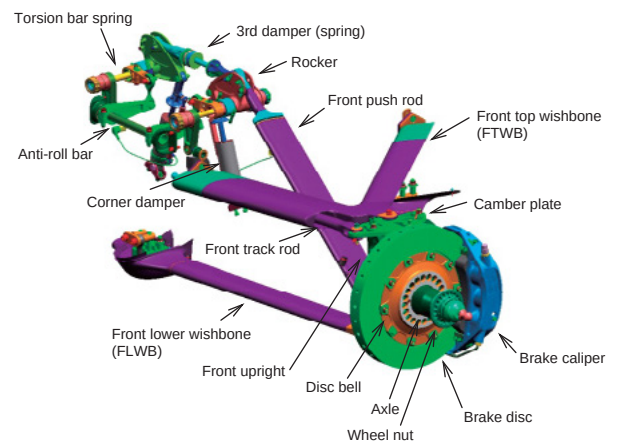


Fig. 9 Front suspension system (2003)

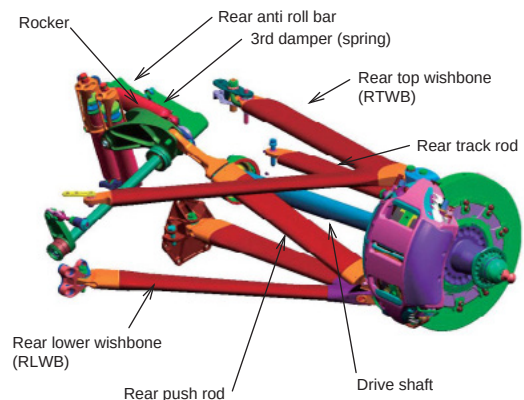


Fig. 10 Rear suspension system (2003)

link generate reaction force in the direction that works to operate the torsion bar. In contrast to this, the structure was changed to link the right and left flat springs with a double end spherical joint as shown in Fig. 11. In this structure, bending force is generated on the flat springs, which deform in the primary bending mode, only in the reverse phase, enabling the same work as that of the conventional structure. In addition, simplification of the structure achieved both weight reduction and enhanced space efficiency.

3.1.2. Development of wheels

The performances demanded of wheels are lightness in weight to minimize the unsprung weight and the loss of turning inertia energy, and high stiffness with respect to the input from tire. However, the ideal balance between weight reduction and high stiffness was not clear, so development was first performed by selecting means of stiffness enhancement by modifying the shape and replacing materials with a minimum impact on weight.

For each suspension part, the degree of contribution to camber stiffness was investigated using bench tests after that, and wheel deformation was found to have an effect. Increasing the camber stiffness and enhancing the camber relative to the ground, even at the expense of weight, was judged to be advantageous for lap time, so development was performed with the target of increasing the camber stiffness of the standalone wheels by 80%. A topology optimization method was used to investigate

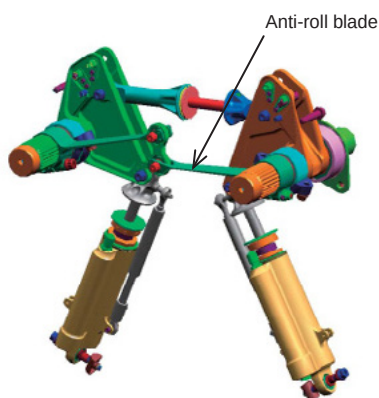


Fig. 11 Front anti-roll blade

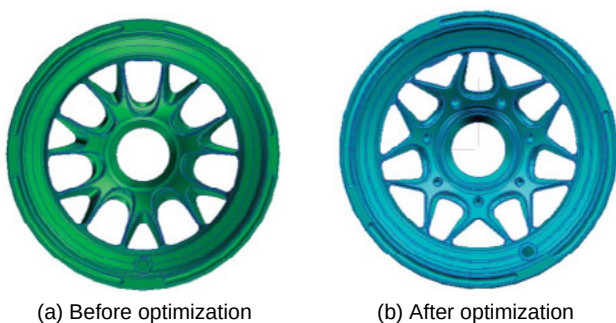


Fig. 12 Wheel spoke topology optimization

the spokes, and the spokes were changed from the shape shown in Fig. 12 (a) to that shown in Fig. 12 (b). This achieved a 56% increase in the stiffness to weight ratio, which reached the target with a weight increase of approximately 10%. The new wheel design was confirmed in track tests to enhance the rear lateral force and rear stability, and was therefore introduced to races.

3.2. Development of Brake Parts

Brake development focused on the issue of how to achieve a high level of balance between the initial braking force, braking force stability, and drag reduction. One method attempted was to reduce the caliper body weight. Formula One regulations stipulate that the caliper body material must have a Young's modulus of 80 GPa or less, so this essentially limits the material to aluminum alloy. Among various aluminum alloys, A2099 was selected, which features good durability (high fatigue strength characteristics), low density, high stiffness, high specific strength, and heat resistance strength. Hydraulic stiffness is important for the caliper body to secure a good pedal feeling, so the center bridge shape was reviewed in consideration of the stiffness balance, and unnecessary material was eliminated from around the cylinder, which succeeded in reducing the weight by 6% (Fig. 13).

3.3. Development of the Water Radiator

Water radiators and oil radiators are mounted in Formula One cars. Water radiators radiate the heat from engine cooling water in the same manner as those in production cars, and are keeping the temperature ranges at high engine efficiency. The cooling water is pressurized to raise the boiling point and to prevent cavitation. Current Formula One regulations stipulate to install a pressure relief valve that opens at 3.75 bars, and this valve is supplied from FIA.

The pressure upper limit is stipulated, and the liquid side heat radiating area has only a small effect, so development of the radiators was performed first for the water radiator side with the goal of weight reduction (Fig. 14). Development was initially started for the qualifying specifications so that priority could be given to weight reduction, even at the expense of durability. Application to the qualifying specifications started from 2001, and the design was repeatedly modified for race use thereafter, and introduced to all races from 2006. Even though the pressure is stipulated, the radiator is still



Fig. 13 Brake caliper

subject to approximately four times the pressure in production cars, so the outside of the stacked tubes is subject to the greatest deformation, and the stress increases in this area. In the initial type water radiator, focus was placed on the heat transfer surface area of the water side, which has a lower contribution to heat radiation performance than the heat transfer surface area of the air cooled side. The inner fins were eliminated, and the outer frame was utilized to suppress bulging in each tube due to the water pressure and the force from the engine. The tube thickness was increased in locations with local increases in stress, and measures were also taken such as reducing the fin thickness, while taking into account pressure resistance. The size was reduced compared to the original base specifications, and performance was enhanced by approximately 9%, which successfully reduced the weight by 37%. However, this structure had its limits when considering a chassis package with enhanced aerodynamic performance, so exclusive tube was developed thereafter. Louver fins were also employed with the aim of increasing toughness against chipping, and together with a greater degree of shape freedom and enhanced durability, achieved further weight reduction of approximately 7% and enhanced heat radiation performance of approximately 4.4%. In addition, boundary layer formation on the water side was considered, and separate specifications that further increase heat radiation performance by approximately 8% was also ready to be applied. Copper, which has a high thermal conductivity, was also investigated as the material, but aluminum was used from the standpoint of weight.

3.4. Development of Titanium Exhaust Pipes

The requirements for exhaust pipe materials are strength, resistance to oxidation, and fatigue strength, when subjected to high temperatures, and a low coefficient of linear thermal expansion. Exhaust does not have a uniform temperature distribution due to the exhaust flow, and resonance also occurs at some engine speeds. Therefore, durability was analyzed and the exhaust pipes were designed in consideration of these effects. That said, exhaust reaches a maximum temperature of 1100 °C, so the materials that can be used are limited, and Inconel is generally used.

A titanium alloy with a low specific weight (density

4.4 g/cm³) approximately half that of Inconel (density 8.5 g/cm³) was used to develop titanium exhaust pipes with the aim of a weight reduction of approximately 30% (Fig. 15). Titanium oxidizes at high temperatures, so development of an anti-oxidation treatment was a key element. The anti-oxidation surface treatment applied was NCC treatment, which consists of first plating parts with aluminum, and then burying the parts in aluminum and alumina powder. This surface treatment generates a uniform Ti-Al alloy layer on the surface of the Ti base material, and oxygen reacts preferentially with aluminum at high temperatures, which enabled the strength of the base material to be maintained. The wear resistance of joint insertion parts must also be increased, so nickel-chromium treatment was applied as surface treatment according to the location. In addition, the exhaust temperature distribution differs according to the exhaust flow and other factors, so also considering the manufacturing efficiency, various Ti materials were used.

Durability of 600 km or more was confirmed by track tests, but not all requirements were satisfied, so the titanium exhaust pipes were not introduced to races.

3.5. Development of Carbon/Carbon (CC) Exhaust Pipes

Like the titanium exhaust pipes described above, which were developed mainly with the goal of weight reduction by material substitution, carbon (CC, density 1.6 g/cm³) exhaust pipes were also developed to further reduce weight. Normal carbon materials have carbon fibers in resin matrix. However, CC is a carbon fiber composite that uses carbon as a matrix. That is to say, CC exhaust pipes are exhaust pipes made of charcoal. Development started with a target durability of 25 laps, aiming for use in qualifying rounds.

The first step was the collector and tail parts, but the ultimate goal was a complete set of CC exhaust pipes including the primary, and a weight reduction target of approximately 39% was set. In addition, conventional exhaust pipes are made by welding together Inconel plate materials. This made it difficult to set a thinner plate thickness, and manufacturability and durability issues meant that excess materials were unavoidable. In contrast, CC exhaust pipes are manufactured using molds, so the minimum thicknesses can be set regardless of welding toughness, and the intermediate sections also



Fig. 14 Water radiator

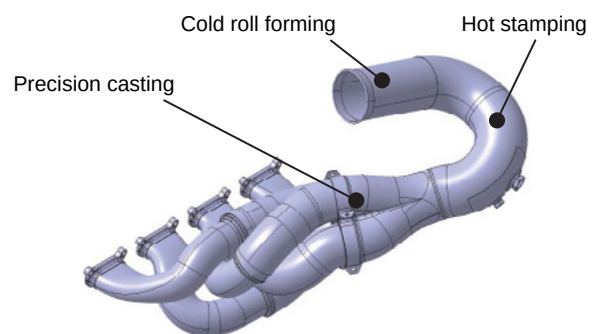


Fig. 15 Titanium exhaust

have a high degree of shape freedom. The final specifications aimed for a compact layout that would be able to enhance chassis aerodynamic characteristics.

In the first step with only the collector and tail parts made of CC, gaps opened at high engine speeds between the CC, which has an extremely low coefficient of linear thermal expansion, and the Iconnel materials used for the primary. This produced the issue that the air-fuel ratio did not stabilize, so a gasket was also developed to fill these gaps that appear at high temperatures. Pure carbon has high heat resistance but low oxidation resistance, and may burn up if measures are not taken, so development of a surface coating to prevent oxidation was a key element. Ultimately, resistance to surface oxidation for 3 hours at 900 °C was successfully secured using a four-layer coating, and durability of 30 laps was confirmed in engine dyno tests, which exceeded the initial target. Efforts were also made at the same time to shorten the manufacturing time, but application only to the qualifying specifications became impossible, so the development was halted.

4. Conclusion

Formula One regulation stipulates a minimum weight of 605 kg, including the driver. Therefore, the weight reduction does not contribute to reducing the absolute weight of the car, but to enhance vehicle dynamics performance, which means increasing chassis competitiveness. This is accomplished by replacing the reduced weight with a ballast to lower the center of gravity, concentrate the weight in the center of the chassis, and expand the longitudinal weight distribution adjustment range.

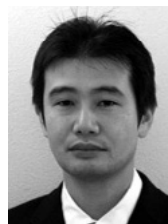
In addition, detailed regulations also stipulate the materials allowed to use, so there is a limit to weight reduction that can be achieved by simple material replacement, which made us to work on approaches such as structural changes based on an understanding of the required functions and performance were needed.

- (1) Reducing the weight of parts located above the car's center of gravity is particularly effective from the standpoint of lowering the center of gravity. This was achieved with the rollhoop, engine cover, water radiator, exhaust pipe, and other parts.
- (2) Reducing the weight of parts that overhang from the front and rear tires is effective from the standpoint of enhancing turn-in performance (reducing the moment of inertia around the Z axis (Izz)). This was achieved with the nosebox, rear impact structure and other parts.
- (3) Reducing the weight of the suspension parts and other unsprung parts is effective from the standpoint of enhancing vehicle dynamics performance, and targeted parts such as the brake calipers, anti-roll bar, and wheels. In addition, not only reducing the weight of these parts, but also stiffness and function enhancements were achieved.
- (4) The monocoque weight was also reduced from the standpoint of optimizing the stiffness.

In this manner, the development was performed to

reduce the Formula One chassis weight, and achieved a certain degree of effects. The development directions and issues in the future was to continue ceaseless development to reduce weight, focusing on higher contributions to reducing circuit lap times, and using ideas conceived during the course of development for further enhancement of functions.

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