Development of Honda Gears for Formula One Gearbox

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ABSTRACT

Development programs were conducted to enable the development of Honda-made gears that balanced low weight and compactness with reliability. Development of a technology for the formulation of gear specifications using FEM analysis and a method of predicting the lifespan of the gears based on S-N curves, which formed the basis for FEM analysis, helped enable continuous short-term development efforts. As gears would sometimes fail in actual vehicle tests, a method of evaluation of lightweight gears optimized for high-load, short-lifespan race use was established with the plastic deformation of the gears as an index. The lightweight, compact, and high-reliability gears developed in this process were employed in races from 2003, and were entirely trouble-free.

In addition, a diamond-like carbon (DLC) coating optimized for race use was applied to all the gear tooth surfaces to boost the performance of the powertrain, helping to achieve a transmission efficiency of 97%. The coating was applied to different gear sets in sequence from 2007.

1. Introduction

At the beginning of Honda's third Formula One era, gears manufactured by a specialist race-gearbox maker were used. However, the top teams were using lighter and more compact in-house gears to increase their competitiveness.

Formula One gearboxes are positioned close to the rear-ends of the vehicles, and their weight makes a significant contribution to dynamic performance. A wide variety of ratio gears is necessary to help enable drive force to be set for each race circuit. In addition, gearbox issues will directly result in retirement from the race. These factors necessitated methods of determining specifications that would reduce the weight of the gears as well as helping to enable accurate prediction of gear life. Regulations freezing engine development also increased the importance of reducing loss in the drivetrain.

In response to these demands, Formula One gear design methods using FEM analysis and standards for quantitative evaluation were formulated, and methods of dealing with exceptional overloads were developed, helping to enable the development of gears that reconciled low weight with reliability. In addition, the transmission efficiency of the gears was identified as the major factor in drivetrain loss, and a DLC coating adapted to race conditions was developed for the gears.

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2. Layout of Formula One Gearbox Internals

Given considerations of vehicle dimensions, aerodynamic packaging, and the stipulations of regulations, a longitudinal two-parallel-axis configuration in which the intermediate shaft (cross-shaft) was positioned one stage upstream from the final reduction gears, was employed for the gearbox internals. Figure 1 shows this gearbox configuration.

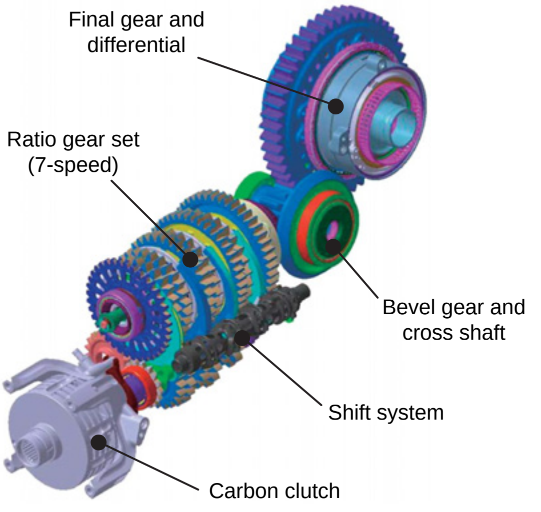


Fig. 1 3D model of Formula One gearbox internals

3. Formula One Gearbox Design Method using FEM Analysis

3.1. Issues of Applying Mass-Production Gear Design Methods to Formula One

The conventional gear design process involves the use of in-house gear specification simulation tools to study gear specifications and evaluate the stresses generated on gear-tooth bottoms. For mass-production gears, it is normal for a specific thickness of the gear-tooth bottoms to be determined by the gear module, and this is used as a precondition for the above-mentioned simulation tools. Formula One gears must balance resistance to extremely high loads and weight saving, even in short lives, in comparison to the gears used in mass-production vehicles, and the concepts used in determining specifications are consequently different. Tooth root strength and pitting strength are necessary in Formula One gears, and the gear modules are therefore increased in size. The thickness of the tooth roots is reduced in order to save weight. The resulting decline in stiffness must be taken into consideration, so conventional design methods were not sufficient to the task. FEM analyses that considered contact between gear teeth were therefore conducted.

Figure 2 shows the difference in shape between a mass-production gear and a Formula One gear.

3.2. FEM Analysis Conditions

Analysis conditions are important in FEM analyses, and in the FEM analyses of spur gears in particular, it is necessary to reproduce the worst-case conditions for a variety of meshing states. The contact gear ratio for the spur gears alternates between 1 and 2, and the gear meshing condition is therefore a continuous sequence of one tooth meshing – two teeth meshing – one tooth meshing. FEM analysis showed that of these, one tooth meshing, and in particular the meshing condition in which the meshing point was highest in the direction of the depth of the gear tooth, placed the greatest stress on the gear tooth root.

Figure 3 shows differences in gear meshing conditions and stress distribution, and Fig. 4 shows changes in the stress on the tooth roots when the meshing phase was altered.

In one tooth meshing, stress concentrates at a single meshing point (Fig. 3), while in two teeth meshing there are two contact points, and the stress concentration is therefore relieved (Fig. 4).

The use of the gear specification simulation to determine from among a variety of tooth meshing conditions the condition in which the stress on the tooth roots was greatest, and the reflection of this result in the FEM analysis, helped to reduce in length the period necessary for analysis.

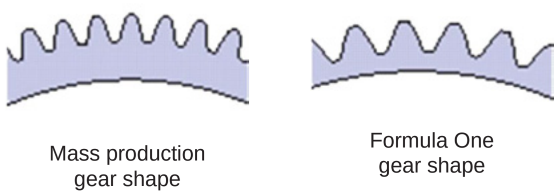


Fig. 2 Gear shape comparison

3.3. Optimization of the Degree of Tip Relief

Tip relief refers to optimizing the form of the gear-tooth tip in relation to an involute curve with consideration of elastic deformation when a load is placed on the tooth. In Formula One gears, the reduction in stiffness mentioned above results in a high level of elastic deformation, which changes tooth contact and has a significant effect on tooth strength and contact face pressure. The level of elastic deformation of the gear teeth tips was therefore predicted using FEM analysis. The degree of tip relief was optimized based on the results.

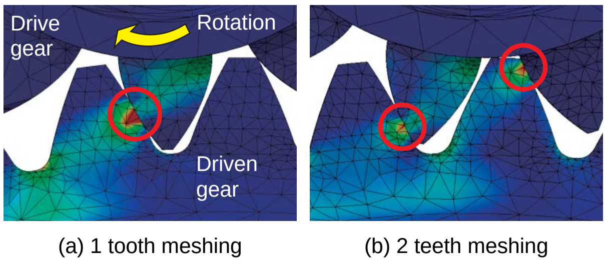


Fig. 3 Gear meshing condition

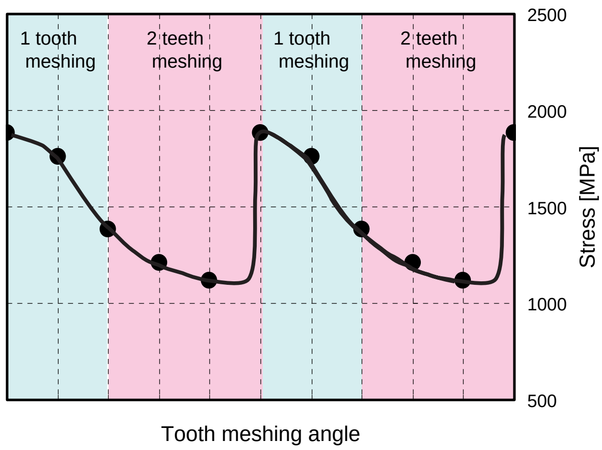


Fig. 4 Change in stress with gear meshing condition

4. Quantitative Evaluation Method for Formula One Gears

4.1. Gear Fatigue Strength Tests

Up to this point, it had been normal to evaluate the durability of race gears using vehicle tests alone. For the development of in-house Formula One gears, however, rig tests of gear units using S-N curves (Wohler curves) and torque frequency measured in actual vehicles were employed in gear evaluation. The reliability of high-load, low-cycle fatigue S-N characteristics represented a concern, but cross-referencing with the results of vehicle test evaluations conducted previously indicated that unit rig tests functioned adequately for evaluations. The determination of gear specifications on this basis helped to enable weight savings to be reconciled with high reliability (Fig. 5). The value of stress at the tooth roots was calculated from input torque, and the S-N curve was formulated based on test results.

4.2. Early Breakage of Gears

The technology for prediction of gear lifespan using rig tests reduced gear breakages, but breakages sporadically occurred earlier than the end of the predicted lifespan of the gears during vehicle tests. Figure 6 shows a representative example of breakage.

When gears that had been used in races were measured, plastic deformation was observed in from one to several teeth (Fig. 7). Given that the plastic deformation only affected part of the gears, it was conjectured that it resulted from instantaneous overloads, and that this resulted in the early breakage of the gears. The phenomenon was therefore analyzed.

Because the amount of plastic deformation was minimal, criteria for judgment of tooth profile data were set, and a difference in the degree of pressure angle correction of 0.2 μm or more was defined as plastic deformation.

Plastically deformed gears were put through fatigue strength tests. The results showed in all cases that the life of the gears was reduced, with the lifespan until breakage only 11.6% of the projected figure in one case (Fig. 8).

4.3. Measures against Overload

In Formula One gearboxes, control is applied to produce an optimum clutch clamp load in order to protect the drivetrain components from instantaneous overloads when the vehicle takes off or shifting is engaged.

Despite this, instantaneous overloads due to inertia and other forces in the gearbox resulting from variations in the clutch friction materials, tire traction on uncertain road surfaces, and irregular steering operation cannot be entirely prevented. However, if gear design incorporated allowances for occasional overloads, increases in weight would be unavoidable, and competitiveness would decline.

In the Formula One gearbox, torque input during vehicle operation was monitored by a torque sensor directly connected to the engine input shaft. The input torque on plastically deformed gears was studied from torque sensor log data. The results, when converted to figures for stress at the gear teeth roots in a simulation, showed that plastic deformation of the gears occurred when the torque input exceeded a threshold of 2300 MPa.

Gear durability tests also showed that plastic deformation occurred at levels of tooth root stress above

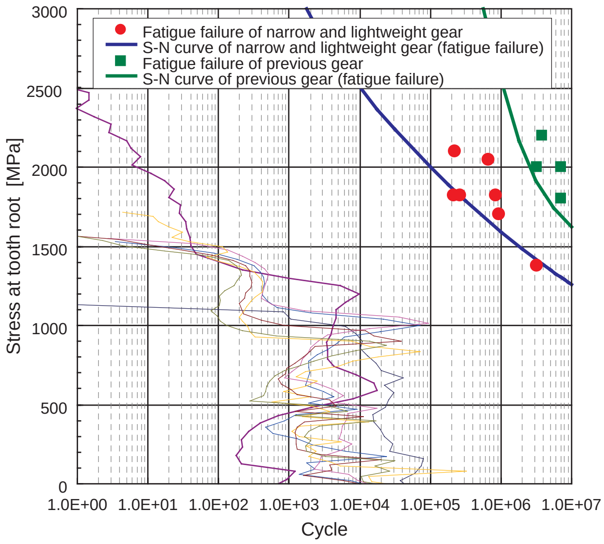


Fig. 5 Fatigue failure test results

Fig. 6 Broken gear

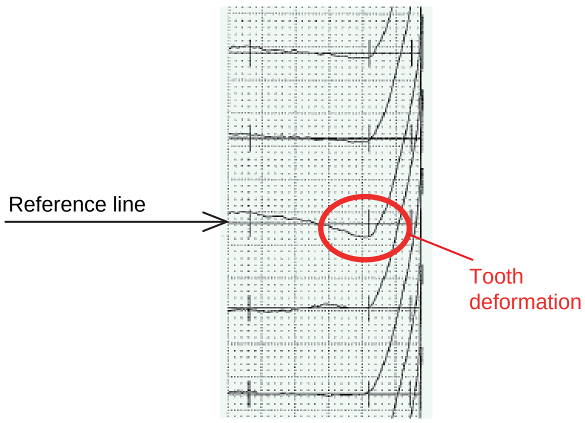


Fig. 7 Tooth profile data of deformed gear

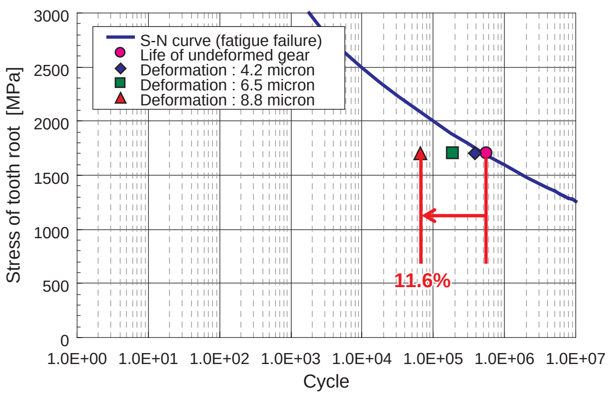


Fig. 8 Fatigue failure test result of deformed gear

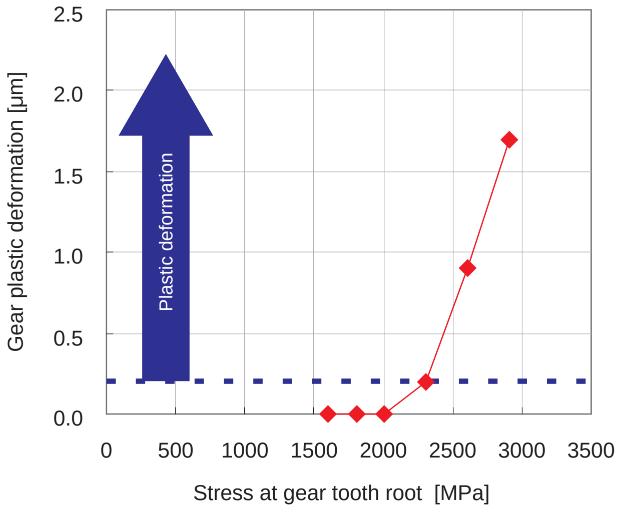


Fig. 9 Gear strength test results

2300 MPa (Fig. 9).

Based on these results, a gear torque limit corresponding to a level of gear-tooth root stress of 2300 MPa was set.

In addition, telemetry data from the torque sensor was monitored in real time, and in the event that a torque input exceeded the torque limit, the relevant gear was replaced during gearbox maintenance.

The measures discussed above helped to reconcile the achievement of low weight with high durability, and the gears were trouble-free during races.

5. Achievement of Increased Efficiency in Formula One Gearboxes

5.1. Analysis of Status of Transmission Loss

A situation analysis of factors in transmission loss was conducted. These factors were isolated by measuring friction in an unloaded state and efficiency in a loaded state (i.e., during transmission). The following factors were identified:

(1) Loss due to oil churning
(2) Loss due to dragging of the oil seals and other parts
(3) Loss due to torque transmission
(4) Oil pump drive loss

Of these, loss due to torque transmission was the reason that loss increased or decreased with the magnitude of torque input. Bearing loss as a factor in transmission loss in a loaded state was calculated using a theoretical formula to separate it from gear transmission loss. Figure 10 shows the rate of contribution of each power loss factor.

These results showed that gear transmission loss was the major factor in gearbox loss, representing 62% of the total figure.

5.2. Methods of Increasing Efficiency

Transmission loss resulted from slipping of gear surfaces against each other during meshing, and could be reduced by reducing the coefficient of friction of the gear surfaces.

The following three methods were available to reduce the coefficient of friction of the gear surfaces:

(1) Reducing the roughness of the gear surfaces
(2) Applying a coating to the gear surfaces
(3) Using a low-friction gear oil

With regard to (1), the gears used in Formula One engines receive a polishing finish and barrel polishing, and no further roughness reduction could be expected. Transmission loss was therefore reduced through (2), the application of a coating to the gear surfaces, and (3), the development of a low-friction oil.

5.3. Selection of Coating Film Type

Under actual Formula One use conditions, the velocity of gear surface slip reaches 20 m/s or more, and gear surface pressure reaches 2 GPa or more. It was necessary to employ a coating which would resist wearing even under these conditions. The gear coating film was selected from among the following candidates:

(1) Metal DLC, which displays good wear resistance, and is used on race engine components
(2) An increased-hardness metal DLC

The following two procedures, which are used to help prevent pitting of the gears in mass-production transmissions and could be expected to reduce the coefficient of friction by increasing slidability, were also included in the comparative study:

(3) Solid-film lubrication (Molybdenum disulfide resin coating)
(4) Sulfurizing

These four coating types were studied for effectiveness in reducing loss and levels of durability. Gears to which only a carburizing treatment had been applied, which were previously standard, were used as a benchmark for comparison.

5.4. Verification of Effects of Coatings and Durability

Figure 11 shows the results of verification of loss reduction in unit rig tests, and Fig. 12 shows the surface condition of gears following durability tests.

Loss was reduced by 2 kW in the gears with the DLC coatings. Some damage occurred to the metal DLC coating, but only minute scuffing of the tips of the gear teeth was observed in the gears with the hardened DLC

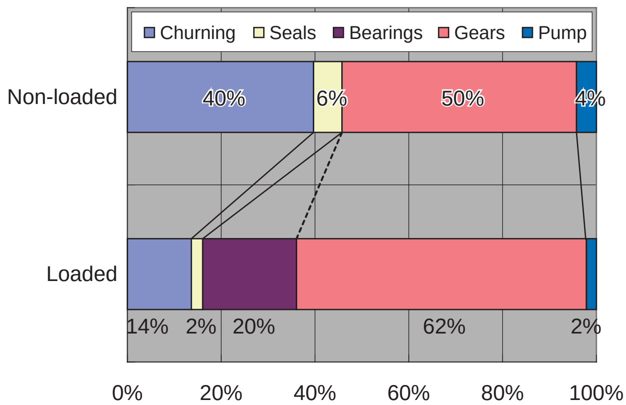


Fig. 10 Effective rate of power loss factors

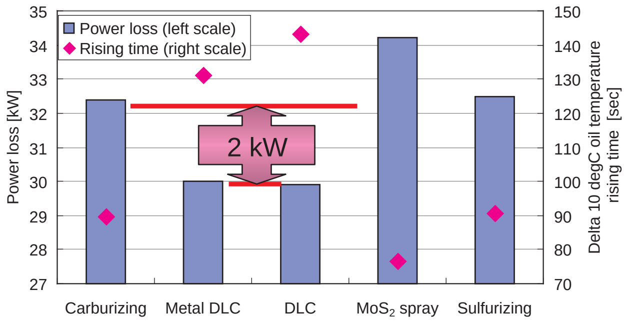
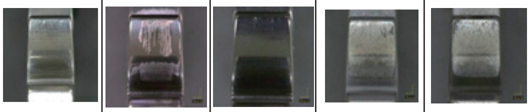


Fig. 11 Confirmation of loss reduction effect



Coating	Carburizing	Metal DLC	DLC	MoS_2 spray	Sulfurizing
Gear surface condition	Teeth touch mark only	DLC peeling DLC wear	Minute scuffing	Coating peeling Gear surface wear & scoring	Gear surface wear & scoring

Fig. 12 Surface condition after durability test

coating, and this did not affect the actual performance of the gears.

Solid-film lubrication and sulfurizing demonstrated no transmission loss reduction effect, and wearing of the coatings was also observed. This is because it is necessary for the surfaces of the gears to be made rougher than the bases in order to apply these coating treatments, and the consequent increase in roughness results in a decline in transmission efficiency.

5.5. Use of DLC Coating in Races

DLC-coated shift gears and final gears were employed in races from the middle of the 2007 race season, and DLC-coated bevel gears were employed from the 2008 season. Optimization of tip relief and the coating pre-treatment helped to enable the achievement of a sufficient level of durability to comply with the regulation that gears must be used for a full four races (Fig. 13).

Fig. 13 Final gear condition after 4 races

5.6. Low-friction Gear Oil

A low-friction oil was developed in cooperation with an oil manufacturer. At the initial stage of the development, reductions of loss of 1 kW or more were obtained in gears without DLC coatings, but when DLC coatings were applied, no loss reduction effects was obtained.

The compatibility between the DLC coating and the oil was therefore examined, helping to enable the development of an oil that reduced transmission loss by 0.4 kW. This oil was used in races from 2008.

6. Conclusion

The following results were obtained from the Formula One gear development program:

(1) A Formula One gear design method using FEM was developed.

(2) Methods of predicting the lifespans of gears in rig tests and of quantitatively evaluating exceptional overloads were developed. These methods formed the basis of a method implemented in gearbox management during races.

(3) A gear coating and an oil were developed that helped to achieve a gearbox transmission efficiency of 97%.

The development results listed above helped to achieve a good balance between function and reliability, and the developed gears demonstrated increased transmission efficiency and produced no gear-related issues during races.

Acknowledgments

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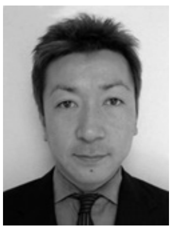
■ Author ■



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