Analysis and Durability Test of Surface Rolled 1P1S 1.5Cr-0.2Mo Very High Density Gear

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Abstract

The load carrying capacities of 1P1S (Single Press Single Sinter) 1.5Cr-0.2Mo very high density (7.5 g/cc) sintered steel gear was tested and analyzed. The P/M gear specimens were machined from sintered packs and some were surface rolled. The bending durability was investigated by single tooth bending fatigue tests. The surface durability was evaluated using a power re-circulation type gear testing rig with a counter pinion gear made of standard grade Ni-Cr-Mo wrought steel. Both of P/M gears and counter pinion wrought steel gears were case carburized and finished by grinding. Failure modes of the tested gears in respect to tooth bending fatigue and rolling contact fatigue were analyzed. The test results show that the high density P/M gears with or without teeth surface densification have high enough durability to replace gears made of typical wrought Cr-Mo steel.

1. Introduction

Automotive power transmission gears necessitate having enough load-bearing capacities to ensure long-term vehicle reliability. Powder metallurgy technology is especially suitable for producing complex shaped parts such as gears. Conventionally processed P/M gears do not fulfill tight tolerances of automotive transmission gears and fatigue strength of them also does not fulfill either, due to the residual porosity. Historically, surface densification by finish rolling has been applied to P/M gears to improve rolling contact fatigue and bending fatigue durability [1-3]. However, since the surface rolling technology is basically based on an empirical approach, the process optimization including preform and tool design is usually very time consuming and requires the several experimental iteration [4, 5]. In addition, recent gear geometries, such as long addendum teeth and large helix angle designed to reduce noise emission, make this optimization procedure more complex and difficult. It is possible only to secure P/M gear accuracies by reducing the amount of deformation in surface rolling or replacing an alternative finishing operation such as shaving. Thus, a fundamental method of solving those optimization problems is the practical application of an advanced high-density P/M gear having a load bearing capacity that is at least equivalent to that of wrought steel gears without surface densification.

In this work, we carried out surface rolling experiments on very high density 1P1S (single press and

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single sintered) P/M gear performs made of 1.5Cr-0.2Mo steel. Then, the load bearing capacity of P/M gears was investigated through gear tooth bending testing in an axial pulsator and gear pitting testing in a force square test rig. Failure modes and endurance limits of this high density P/M gears and the effects of surface rolling or shot peening on the load bearing capacity were determined. The purpose of this study is to examine the deformation behaviors of this new P/M steel in gear surface rolling and to assess the fatigue strength for the applicability as a transmission gear material.

2. Experimental method

Table 1 shows the chemical composition of two kinds of tested P/M material. The Fe-2Cu-0.8C (called FC-0208 hereafter) is made from the mixed powder. The Fe-1.5Cr-0.2Mo-0.23C (called FL520X hereafter) is made from the completely pre-alloyed powder to bring the composition close to the wrought alloyed steel of SCM415 in JIS, which corresponds to DIN15CrMo5 most commonly used for transmission gears. The carbon content of FL520X is suppressed relatively low with 0.23% to control the work hardening and to improve the surface densification properties by surface rolling. The comparison of P/M steel characteristics in each material is shown in **Table 2**, which indicates that the FL520X has very high density and low porosity comparing with the conventional FC-0208 and is the very target material of this work.

Gear surface rolling experiments and endurance limit tests were carried out using P/M spur gears. We prepared one kind of FC-0208 gear of GL and three kinds of FL520X gear of GH, GHR and GH WPC. The dimensions and process routes of P/M gears and counter pinions are summarized in **Table 3**. The surface rolled P/M gears GHR were cut by the modified hob to obtain a pronounced convex tooth profile around the pitch point as shown in **Figure 1**, which was designed to get a true involute tooth profile after surface rolling. Other test gears of GL, GH and GH WPC were cut by the standard hob without surface rolling. WPC is a special shot-peening process added after carburizing by firing ultra fine particles towards the gear tooth surface at very high speeds [6]. Rolling experiments were conducted using a high precision two-roller dies transverse form rolling machine FA-20/CNC developed by Nissei Co. Ltd. **Figure 2** shows the surface rolling state of a P/M gear. In this process, only the right side tool is pushed radially into the P/M gear until a pre-set center distance between the right and left tool spindles is reached. A tool rotation speed of 60 min^{-1} and a tool indentation speed of 0.167 mm/rev were employed. As the amount of maximum radial tool displacement r_0.was set to 1.50 mm, the net processing time was less than 10 seconds. Gears of FL520X used in fatigue test were case carburized under the condition as shown in **Figure 3** and the FC-0208 gear GL was normalized. **Figure 4** shows the micro-hardness profile around the pitch point of GH and GHR. Those effective carburizing depth are about 0.6 mm.

For investigation of the load carrying capacities of P/M gear, single tooth bending fatigue (STBF) tests and gear pitting tests were carried out. **Figure 5** shows the schema of the STBF test machine. The load P_n was applied at the tooth tip of the gear in pulsating bending and the operating speed was set to

Table 1. Chemical composition (wt. %) of the test gears and test rollers

Material	C	Mo	Cr	Cu	Fe

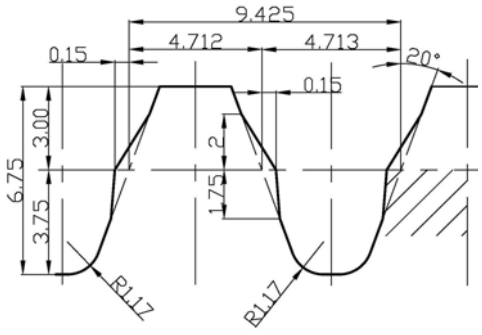


Figure 1. Modified Tooth profile of P/M gear

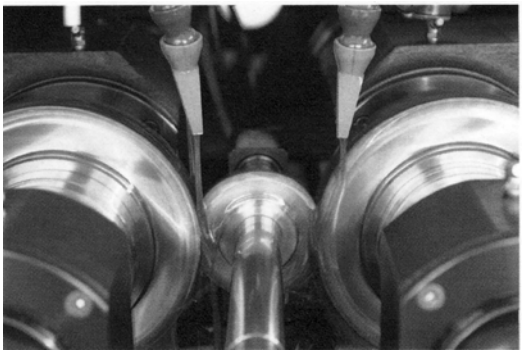


Figure 2. Gear after finished rolling cycle

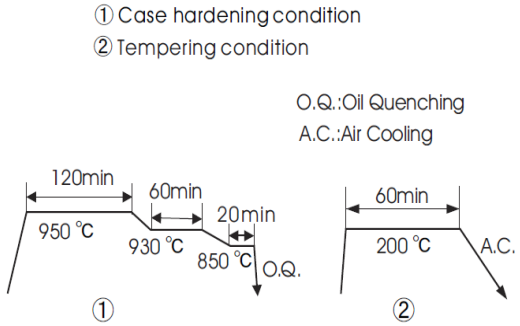


Figure 3. Carburizing condition

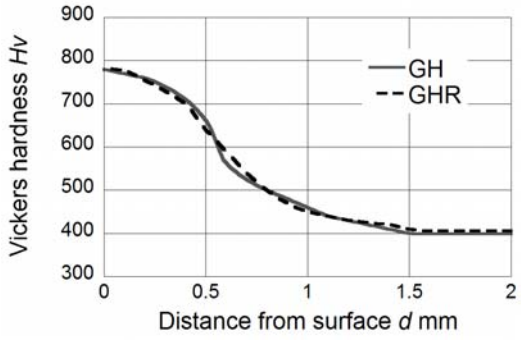


Figure 4. Micro hardness profile of test gears

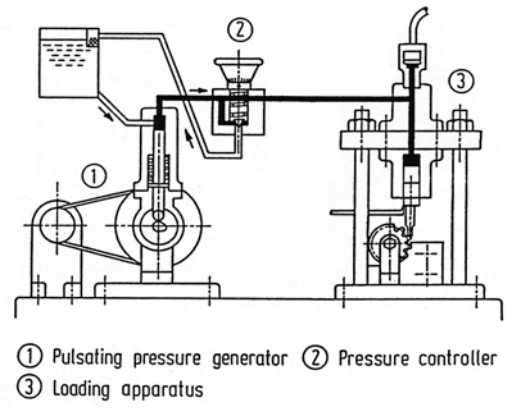


Figure 5. Schema of STBF test machine

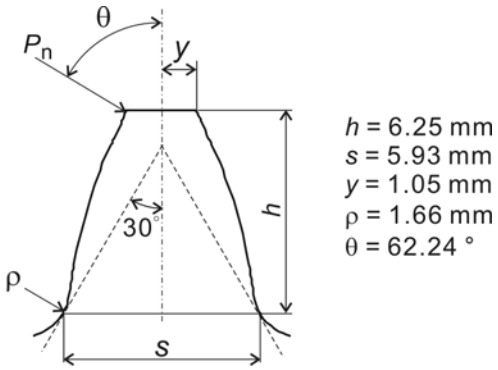


Figure 6. Typical Dimensions of STBF test gear

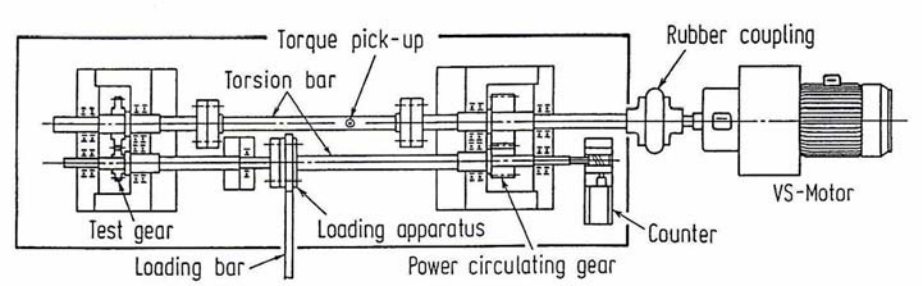


Figure 7. Power re-circulating type gear pitting test rig

710 cycles per minute. The test was stopped at 5×10^6 cycles and considered a non-failure if the tooth had not broken. **Figure 6** shows the typical dimensions of STBF test gear of which values are set as shown in the figure. The tooth root bending stress σ_t was calculated by the following equation proposed by Aida and Terauchi [7].

$$\sigma_t = \frac{AP_n}{mb} \tag{1}$$

where, A is the influence coefficient of root bending stress, m is the gear module [mm] and b is the tooth width [mm]. Gear pitting tests were conducted using a power re-circulating type test rig as shown in **Figure 7**. A 3.7 kW variable speed motor was used as a power source. The maximum re-circulating power is 10 kW. Test gear speed in this experiment was n = 900 /s (pinion speed = 1800 /s). The mineral lubricating oil of RO150 (made by Nippon Oil Corporation.) which kinematic viscosity is 150 mm^2/s at 313 K and 14.6 mm^2/s at 373 K was supplied at a rate of 0.4 L/min at a temperature of 313 K. The corresponding grade of RO150 is 150 in ISO-VG, 90 in SAE and 4 in AGMA. The running-in before an actual pitting test was done in a light loading condition of 50% of endurance limit for 10^5 loading cycles. The contact fatigue life was defined as the number of load cycles at which 2% of the tooth surface of the test gear was pitted, and the run-out limit was set to 1.5×10^7. The surface contact stresses of gears at the pitch point were evaluated by the Hertz stresses that arise from the contact pressure of two contacting cylinders which have the same radii of curvature of the gear teeth involute surface [8]. The maximum surface compressive stress σ_H is given by

$$\sigma_{\mathrm{H}} = \sqrt{w(R_1 + R_2) / \left[\pi R_1 R_2 \left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \right) \right]} \qquad (2)$$

where, w is load per unit length [N], R is radii of curvature of each cylinder [mm], E is Young's modulus [GPa] and ν is Poisson's ratio. E and ν for the FL520X gear are assumed to be 190 GPa and 0.29 respectively. **Figure 8** and **9** show examples of typical tooth profile and lead curves of a P/M test gear and a counter pinion used in pitting tests. The tooth profile and lead errors are very small and those accuracies are corresponding to DIN 5 grade. The flank surfaces of both test gears were finished by grinding to be the maximum height surface roughness $Rz < 2$ μm.

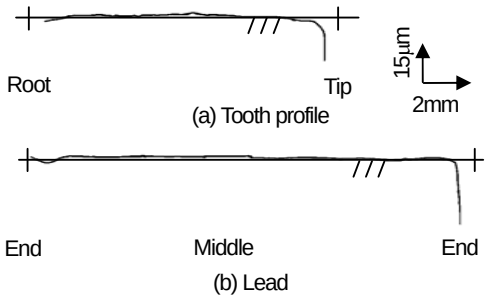


Figure 8. Tooth profile and lead curves of P/M gear

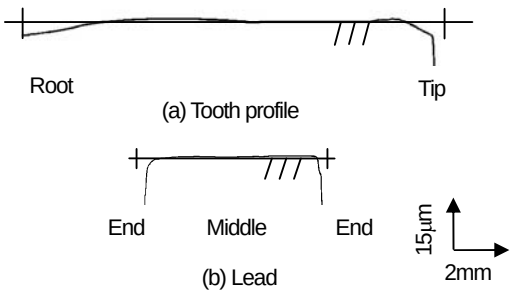


Figure 9. Tooth profile and lead curves of pinion

3. Results and discussion

Figure 10 shows examples of tooth profiles and leads of gears after surface rolling. This is for the case of FL520X gear GH. As the amount of tool radial displacement r_0 increases, the tooth profiles gradually align with the true involute. P/M gears with good involute tooth profile on both driven and follow sides can be obtained by optimizing r_0. On the other hand, the tooth lead profiles are kept almost flat regardless of r_0. The same deformation pattern was observed for the FC-0208 gear GL. **Figure 11** shows the comparison of microphotographs of sintered metal porosity around the pitch point of test gear. The size of pores of FL520X is considerably smaller than that of FC-0208, and its densification level is very high. Specifically, at the surface and to a depth of approximately 0.5 mm, the densification property of FL520X is very benign. The porosity distribution around the pitch point of surface rolled FL520X gear GHR is shown in **Figure 12**. Note that the material in the gear surface layer at a depth of

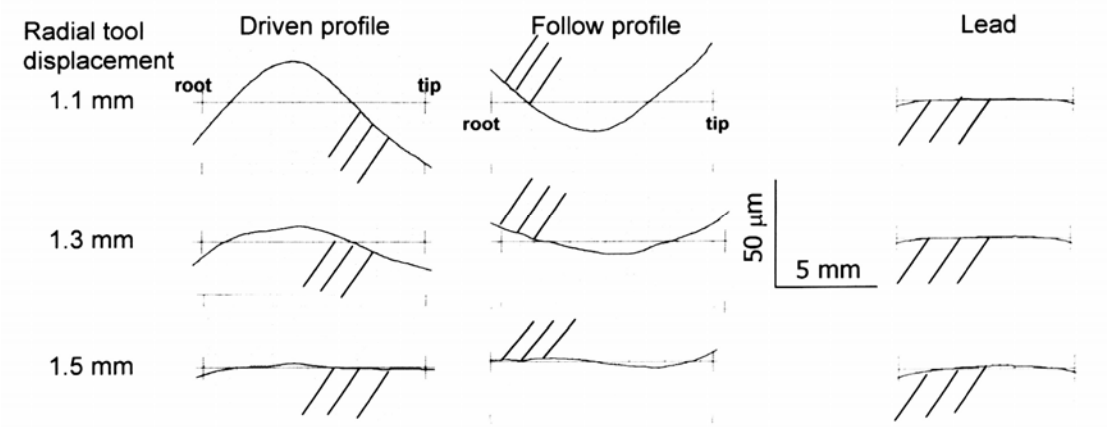
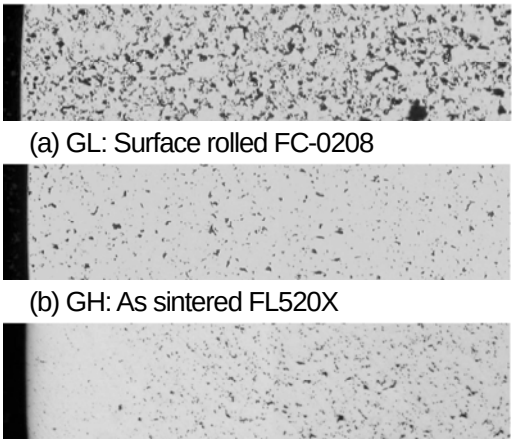


Figure 10. Tooth profile and lead curves after rolling of P/M gears of FL520X

about 0.5 mm is fully dense. These densification properties seem ideal to improve surface fatigue strength, since the maximum shear stress in sliding rolling contact typically acts under the surface at a depth of 0.2 mm depending on contact width and the magnitude of friction.



(a) GL: Surface rolled FC-0208

(b) GH: As sintered FL520X

(c) GHR: Surface rolled FL520X

Figure 11. Microphotographs of P/M porosity

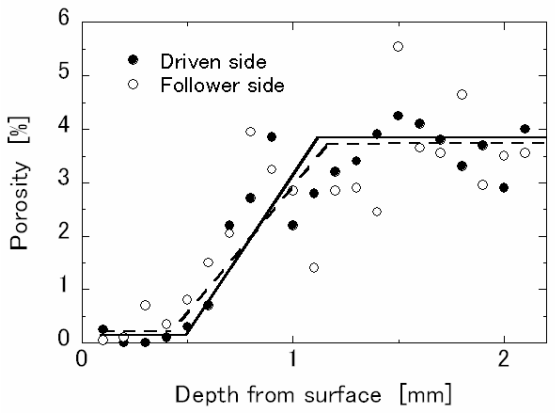


Figure 12. P/M porosity profile around pitch point of Surface rolled FL520X GHR

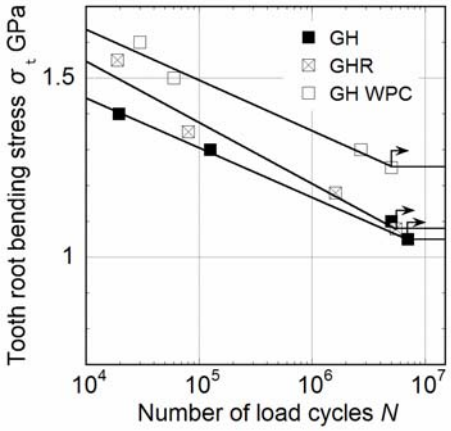


Figure 13. Bending fatigue test results

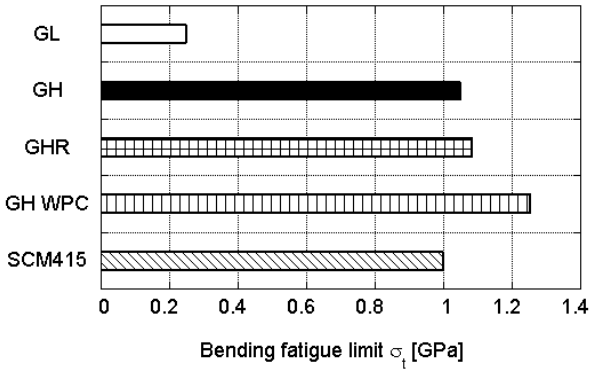
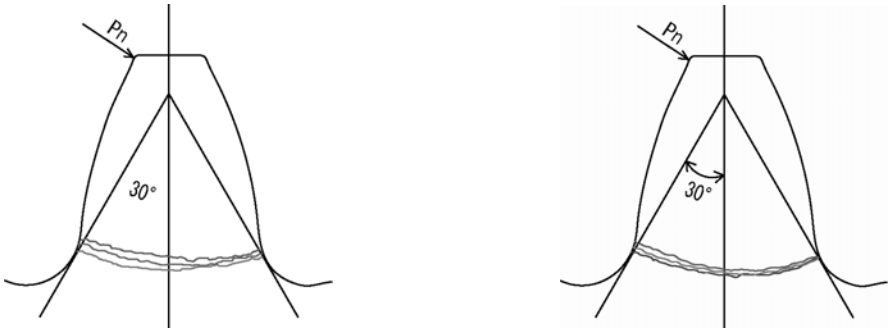


Figure 14. Bending fatigue limits of test gears



(a) GH: As sintered FL520X (b) GHR: Surface rolled FL520X

Figure 15. Bending fatigue cracks of test gears

The load carrying capacities of the P/M materials are compared with those of typical wrought steel SCM415 in JIS which corresponds to DIN15CrMo5. **Figure 13** summarizes the test results of STBF and **Figure 14** shows the comparison of bending fatigue limits of test gears. The bending fatigue limit

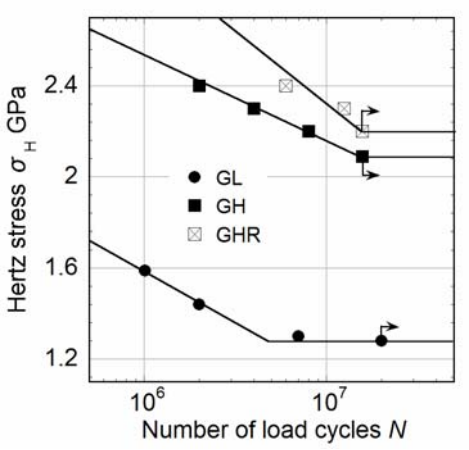


Figure 16. Gear running test results

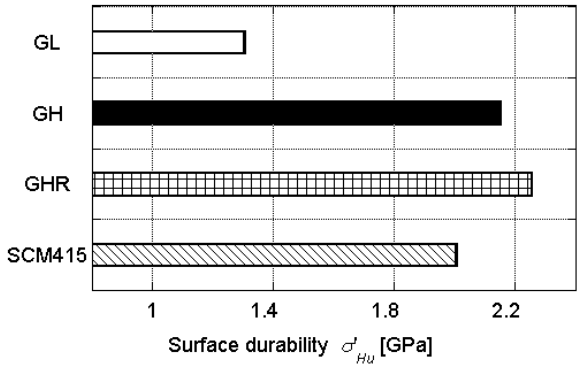
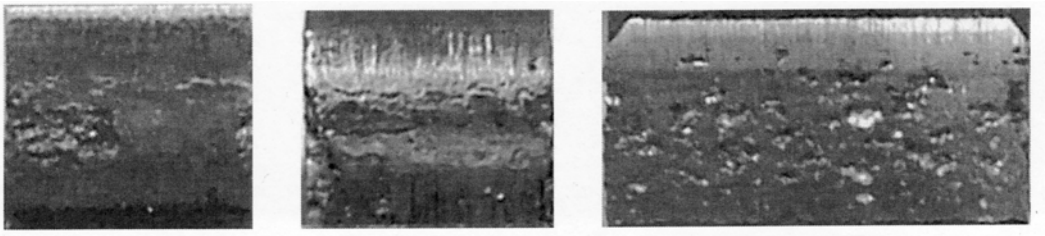


Figure 17. Surface durability of test gears



(a) GH, σ_H=2.4 GPa (b) GHR, σ_H=2.4 GPa (c) GL, σ_H=1.3 GPa

Figure 18. Surface failures of test gear

of FC-0208 gear GL is far below that of the wrought steel gear. On the other hand, the strength level of FL520X gear GH, as-sintered and casehardened, is equivalent to that of the wrought steel gears, and is much improved about 20% by WPC. However the bending fatigue limits is slightly increased by surface rolling, since the roller die tool is not optimized to densify the fillet surfaces in the root near the most critically stressed point. **Figure 15** shows the bending fatigue cracks in STBF tests. The positions of crack initiation are the Hofer's critical section in every case and every crack propagates along the weakest cross section to the critical section of the opposite tooth surface.

Figure 16 summarizes the gear running test results and **Fig. 17** shows the surface durability of test gears. Failures of test gears were pitting. Thus, the load bearing capacity of a P/M gear is dominated by the surface durability. The surface durability of as sintered FL520X gear GH is considerably higher than that of FC-0208 gear GL, and is also higher than that of the case-carburized wrought steel gear of SCM415. The amount of increase in surface durability of surface rolled FL520X gear GHR is only about 5% compared with un-rolled GH. **Fig. 18** shows failures on gear tooth surface. Pitting failures occur near the pitch point of FL520X gears GH and GHR as is the case with wrought steel gears. On the other hand, failures appear on the whole tooth surface for the FC-0208 gear GL. This might be caused by large pores scattered on the tooth surface of low density sintered steel.

4. Conclusions

- A high precision form rolling machine enables sufficient control to make spur gears with accurate

shape and a fully densified surface layer of at least 0.5 mm on the gear flank for high density Cr-Mo P/M steel gears.

- The strength level of FL520X gear, as-sintered and casehardened, is equivalent to that of case-carburized wrought steel gears made of typical Cr-Mo alloyed steel and is much improved by about 20% using WPC.
- The pitting resistance of high density Cr-Mo P/M gears without surface densification is completely matches those of case-carburized wrought steel gears made of typical Cr-Mo alloyed steel and its surface durability tends to increase by surface rolling.
- The very high density and high performance 1.5Cr-0.2Mo sintered steel has enough load-bearing capacities as the automotive transmission gear material.

5. References

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